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**ADVANCED BATTERY SYSTEM FOR
AIRCRAFT**



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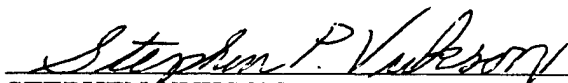
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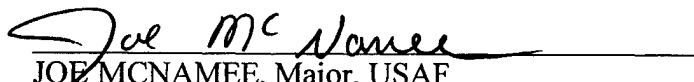
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1.0 Introduction

This is the final report on the Advanced Battery System For Aircraft (contract F33615-86-C-2678). This report contains final design and test data on the aircraft battery system and its components developed under this contract by Eagle Picher Industries, Inc. (EPI) (battery development) and ELDEC Corporation (charger/controller development).

Figure 1-1 shows the basic battery system. It contains three elements: Battery, Battery Charger, and Controller. Physically the controller and the charger are housed in one Line Replaceable Unit (LRU). The aircraft interface with the battery system consists of a power interface; three phase input power required is 115Vrms line to neutral at 8A per phase, 400Hz ac bus, and output power is 28Vdc battery bus capable of handling 50A currents. The signal level interface with the aircraft system is in the form of LED drivers for fault and status indication.

2.0 Program Objective

2.1 Discussion

The current state-of-the-art aircraft batteries (vented nickel cadmium and lead acid) are not capable of meeting the desired low maintenance requirements of today's Air Force. Currently used aircraft batteries have a routine maintenance interval period of approximately 90 days, with some cases of high rate type applications needing weekly maintenance cycles.

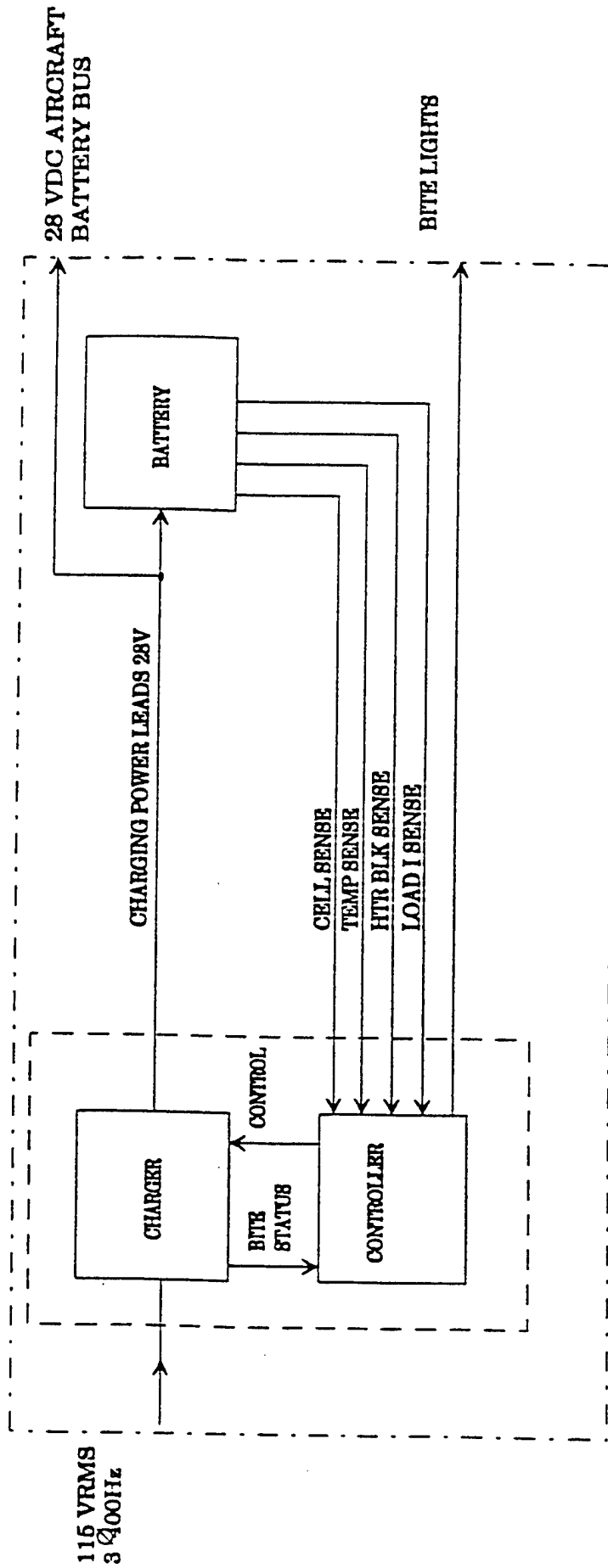
2.2 Objective

The objective of this effort was "to develop the technology for an advanced aircraft battery system, consisting of a sealed nickel cadmium battery module, a charger module with a microprocessor monitor/self test module that is suitable for use in a broad spectrum of Air Force aircraft applications." This program would address the logistical need to eliminate field maintenance battery shops and flight line maintenance activities necessary for currently used systems. The system was to be designed with the intent of operating for 3 years or 1000 flying hours without maintenance.

2.3 Statement of Work

The objectives for this contract are detailed in the Statement of Work (F33615-86-C-2678), and are summarized below.

- 1) Meet the program design goal that the battery system must have a three year or 1000 flight hours maintenance free operation.
- 2) Issue a report on Air Force aircraft battery usage and maintenance requirements. This report was generated and released by EPI reference System Trade-Off Study dated August 15, 1989.



SYSTEM BLOCK DIAGRAM

FIGURE 1-1

JB101.DRW

- 3) Develop an Advanced Battery System Specification Control Drawing(SCD). ELDEC SCD 4-520 was developed to define the requirements for the hardware to be delivered at the end of the contract.
- 4) Develop a sealed NiCad battery technology applicable to an aircraft environment for the 0 to 50 Ahr range.
- 5) Develop a microprocessor controlled charger/controller to provide battery charging and battery system monitoring.
- 6) During the program, monthly status reports were provided to update the progress of the work.
- 7) Present a Preliminary Design Review (PDR) and a Critical Design Review (CDR). During the program there were two reviews where government and industry personnel were invited to evaluate the design for the advanced battery system. These were held in Colorado Springs, CO (Battery CDR, Charger/Controller PDR) in Aug 89, and in Bothell, WA (Battery update, Charger/Controller CDR) in Mar 90.
- 8) The extension to the contract to support flight testing for B-52, E-3, and AC-130 aircraft types will not be covered in detail in this report. A flight test report for each of the aircraft is attached as Appendixes A and B.

3.0 Conclusions and Recommendations

All of the program objectives were met. The deliverable systems are designed to have maintenance free operation for 3 years or 1000 flight hours. The goal of achieving a sealed NiCad battery and a microprocessor controlled charger was also met. Although the contract scheduling required ELDEC and EPI to perform much of battery and charger development in parallel, at program end an integrated and reliable system was delivered.

As with any research or design work, there were trade-offs to be made during the development of the hardware. In the case of the Advanced Battery System a listing of lessons learned or recommendations is presented. These items are suggestions for improvements to the existing design for a potential second phase or follow on contract.

3.1 Battery Recommendations

Overall, the batteries met all requirements of the Program Objectives as set forth by the Statement of Work. Nonetheless, continuous improvements and upgrades to material and processes are being sought to provide a better product.

3.1.1 Separator Material

In batteries bearing Eagle-Picher part nos. 18213 and 18214, polyolefin was used for the separation material. In part nos. 18216 and 18192, polypropylene impregnated with Polybenzimidazole (PBI) was used as separation material. Due to the favorable

results from testing 18216 and 18192, Eagle-Picher recommends that polypropylene impregnated with PBI be used as separation material.

3.1.2 Resealable Vent Plug

Original specifications on the Advanced Battery System for Aircraft resealable vent plug were for venting to occur at 90 psi and to reseal at 60 psi. These parameters were found to be inappropriate and the final design was set for venting at 75 psi and reseal at 45 psi.

3.2 Charger/Controller Recommendations

3.2.1 Downloading Data Save RAM

Currently the only way to download the data from the Data Save RAM is to take the system off of the aircraft. Once off the aircraft the data must be downloaded with a special piece of test equipment which will print the data on paper. To improve this process ELDEC proposes that a future charger/controller have a serial interface connector that could be accessed while the unit is on the aircraft. The data could then be downloaded from the charger/controller to a portable computer. This would solve the problem of removing the unit from the aircraft, and would allow for electronic storage of the data.

3.2.2 "Keep-Alive" Battery

The method used to store data and keep track of real time requires a small battery in the charger/controller for memory back-up. From a maintenance standpoint this is a weak link in the design. At the current size of the back-up battery, it would need to be replaced every 3 years to ensure proper operation. For the next generation charger design ELDEC proposes to modify the method of storing data such that the "keep-alive" battery is not required. There are several ways to provide the same function while extending the maintenance life considerably.

3.2.3 Power Draw from the Aircraft Battery

The system Specification Control Drawing (SCD 4-520) calls out a maximum current draw on the aircraft battery of 100mA for the charger. The charger/controller meets this requirement; however, for low amp hour systems this is somewhat excessive. For the next generation charger design ELDEC proposes a design goal of less than 25mA.

3.2.4 Power Stage Design

The power stage design for the charger/controller utilizes a mature technology in both the topology and the power component selection. As such it contributes to the large size of the charger/controller. ELDEC proposes that a follow-on contract require a more progressive design approach for the power stage circuitry. A new approach could utilize state-of-the-art power semiconductors and high frequency design techniques to minimize the size of the power magnetics.

3.2.5 High Density Packaging

The current design of the charger/controller utilizes conventional through-hole plated technology circuit boards and hand wired interconnects. To further reduce the size of the charger/controller, on the next generation design, the use of high density packaging is recommended. This could be either hybrids or Surface Mount Technology for circuit boards, and flex strips for board-to-board interconnects.

3.2.6 Modular Design concepts

The greatest determinant of the size of power conversion equipment is its power level. The charger/controller built for this program is designed to deliver 30V at 50A. This is appropriate for a 40 to 50 Ahr battery; however, for a 10ahr battery it is excessive. ELDEC proposes that the next generation of charger/controller be made from a family of smaller, lower power modules at output levels of perhaps 10, 30 and 50A which could be paralleled to provide higher current applications. Thus, the charger/controller would be truly modular in both the control and power aspects, with software control that could be easily modified for different control schemes or battery types, and plug-in power modules to support different battery sizes.

4.0 Battery Design

4.1 Designs Evaluated

Three different types of batteries were evaluated to find which of the three would be most suitable for this project. They were starved electrolyte, semi-starved electrolyte, and flooded electrolyte/negative limited.

4.2 Design Selected

As the goal of this contract was to produce a battery system that would reduce maintenance and increase life cycle, the starved electrolyte battery design was found through testing to be the most suitable for this project. There were four different batteries used and they are described below:

EPI 18213. A 20 cell nickel cadmium battery with a capacity of 23 ampere hours. This battery uses the EPI-3223 cell, which is manufactured using the dry sinter process. Polyolefin was used for separating material. Cells were activated with 1.30 specific gravity KOH. This design was flight tested on the B-52.

EPI 18214. A 10 cell nickel cadmium battery with a capacity of 55 ampere hours. This battery uses the EPI-3160 cell, which is manufactured using the dry sinter process. Polyolefin was used for separating material. Cells were activated with 1.30 specific gravity KOH. This design was flight tested on the E-3.

EPI 18216. A 20 cell nickel cadmium battery with a capacity of 40 ampere hours. This battery uses the EPI-4240-1 cell, which is manufactured using the dry sinter process. Woven nylon and Celguard was used for separating material. Cells were activated

with 1.30 specific gravity KOH. This design was flight tested on the AC-130.

EPI-18192. A 20 cell nickel cadmium battery with a capacity of 24 ampere hours. This battery uses the EPI-2024-1 cell, and is also manufactured using the dry sinter process. Woven nylon and Celguard was used for separating material. Cells were activated with 1.30 specific gravity KOH. This design was also flight tested on the AC-130.

Nylon cell casings were used on all four batteries. The 18216 and 18192 were vented cell batteries. The 18213 and 18214 were fitted with a resealable vent system. The vent system was designed to open when pressure reached 75 psi, and then reseal when the pressure lowered to 45 psi.

5.0 Charger/Controller Design

The charger/controller provides both battery charging and battery system monitoring functions. The basic operation for our 23 Ah battery system is described below.

Battery charging is accomplished by the following method:

Basecharge -	constant current at approximately 2C rate.
Topping Charge -	constant current at approximately C/2 rate.
Float Charge -	constant voltage at 26.5V.

Basecharge and topping charge are terminated when the battery voltage reaches a temperature compensated cut off level.

Monitor functions include the following:

Charger Module -	Overcurrent Overvoltage Undervoltage Input power Input commands
Controller Module -	Microprocessor check Input power Operation date and time "Keep-Alive" battery check
Battery -	Battery temperature Cell overvoltage Cell undervoltage Battery heater blanket Battery load currents

5.1 Electrical Design

The charger module contains the power electronics to provide the proper output voltage and current to the battery for charging. The controller module is microprocessor controlled and contains the software for charger control, Built In Test (BIT), and battery monitor functions.

5.1.1 Charger Design

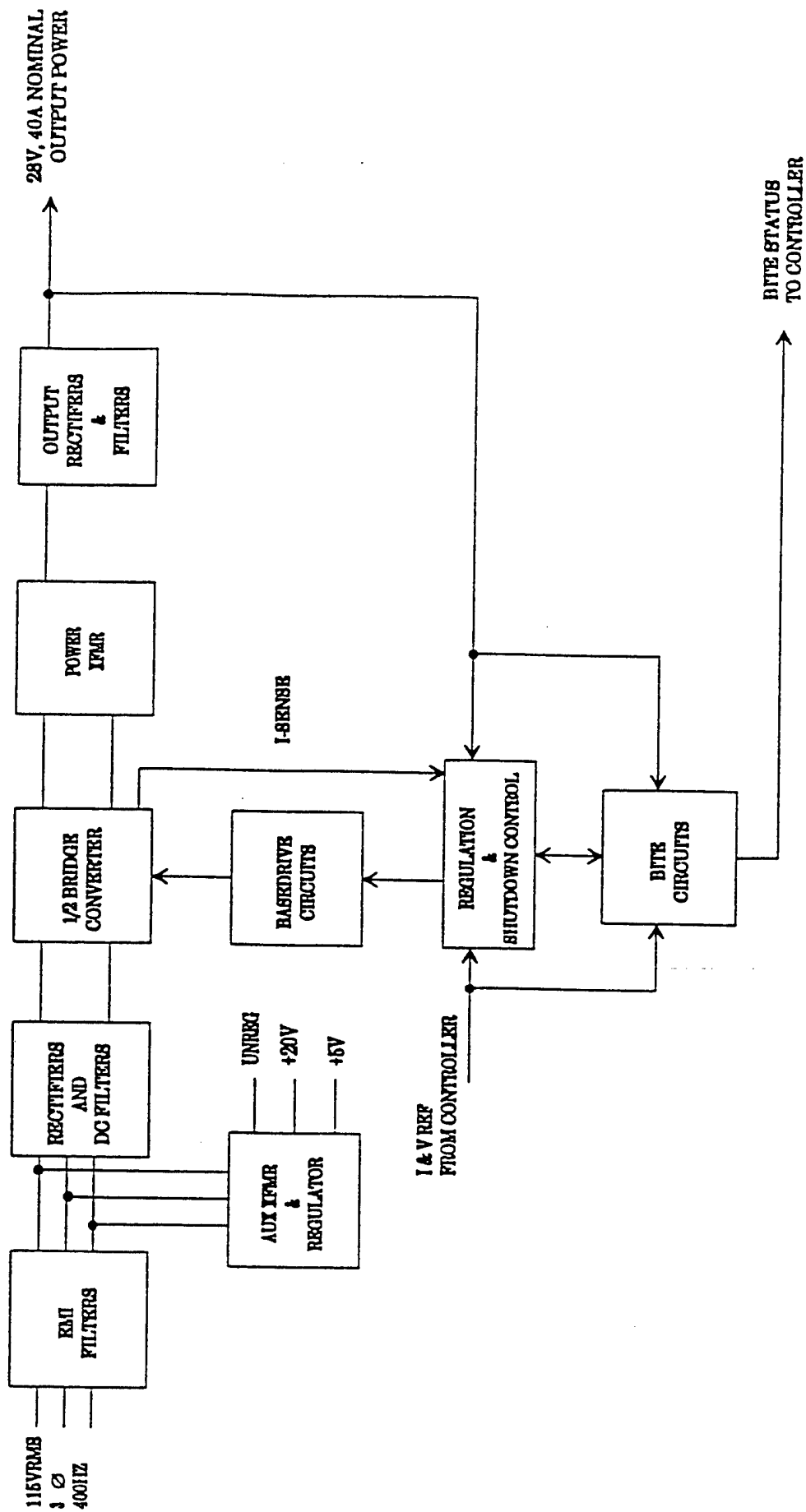
The charger module used for this program is a modified version of a design that ELDEC has been using for aircraft chargers. This design was chosen because it is passively cooled, and covers the power range required by this project (0 to 50A). Design emphasis was on the controller, with goal of control methods and battery monitoring that could be much "smarter" than existing systems. The physical size of the charger is driven by its power capability and the resultant passive cooling techniques described in section 5.2.1.

Figure 5-1 shows a block diagram of the charger module. The input power for the charger is standard aircraft three phase, 115Vrms, 400Hz power. The Electromagnetic Interference (EMI) filters provide filtering to protect both the charger and the input power. The filters provide protection for the charger by filtering input spikes from the main generator lines. The filters also provide attenuation of the switching noise generated by the input rectifiers and the auxiliary regulator. This filtering attenuates noise conducted from those sources.

The input rectifiers convert the 400Hz ac input into a dc input with a 2400Hz ripple component. The dc filters smooth out the 2400Hz ripple component and attenuate the high frequency switching noise from the half-bridge converter. This filtering also provides EMI protection for the input line.

The half-bridge converter segments the input dc voltage and provides an AC high frequency voltage across the power transformer. This method allows the use of smaller power transformers as transformer size is inversely proportional to operating frequency.

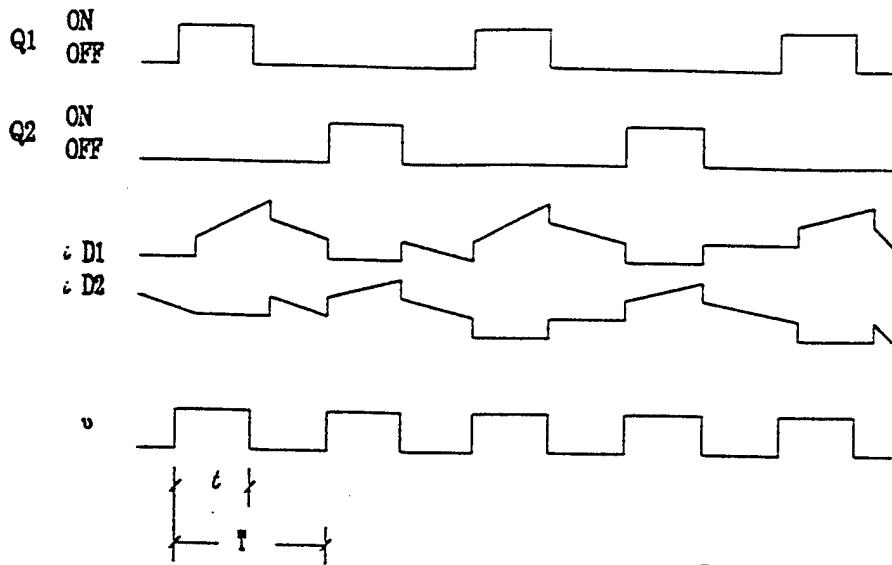
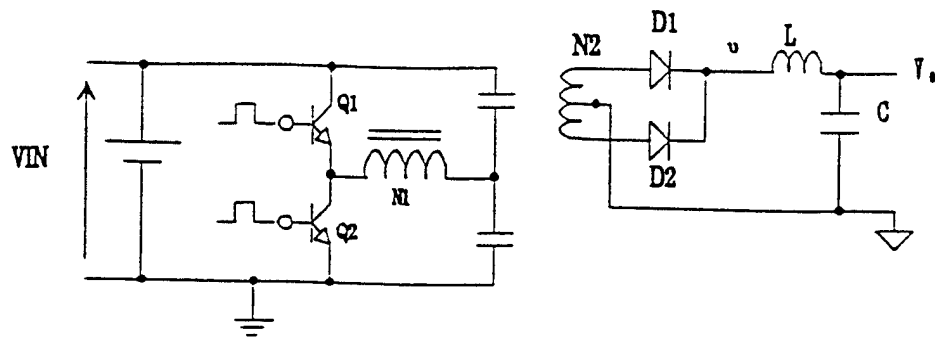
This ac voltage is transformed to a lower ac voltage via the power transformer and then full wave rectified and filtered to provide the final dc voltage and current required by the battery for charging. The half-bridge converter is based on a common buck type regulator topology. Figure 5-2 pictorially describes its operation. As shown in the figure, when either Q1 or Q2 are on there is a voltage applied to the output filter LC. This filter averages the rectified voltage, V , applied to the filter. The resultant output voltage is a function of the input, V_{in} , the transformer turns ratio, and the duty cycle of the applied waveform. This duty cycle is controlled via the control circuits to be described later. When both transistors are off the two output diodes continue to conduct because there is a dc current in the output inductor, L , which continues to flow. This is the



CHARGER MODULE BLOCK DIAGRAM

FIGURE 5-1

JB401.DRW



$$\text{DUTY CYCLE} = \frac{t}{T} = D$$

$$V = V_{IN} \left(\frac{N2}{N1} \right) D$$

HALF BRIDGE CONVERTER WAVEFORMS

FIGURE 5-2

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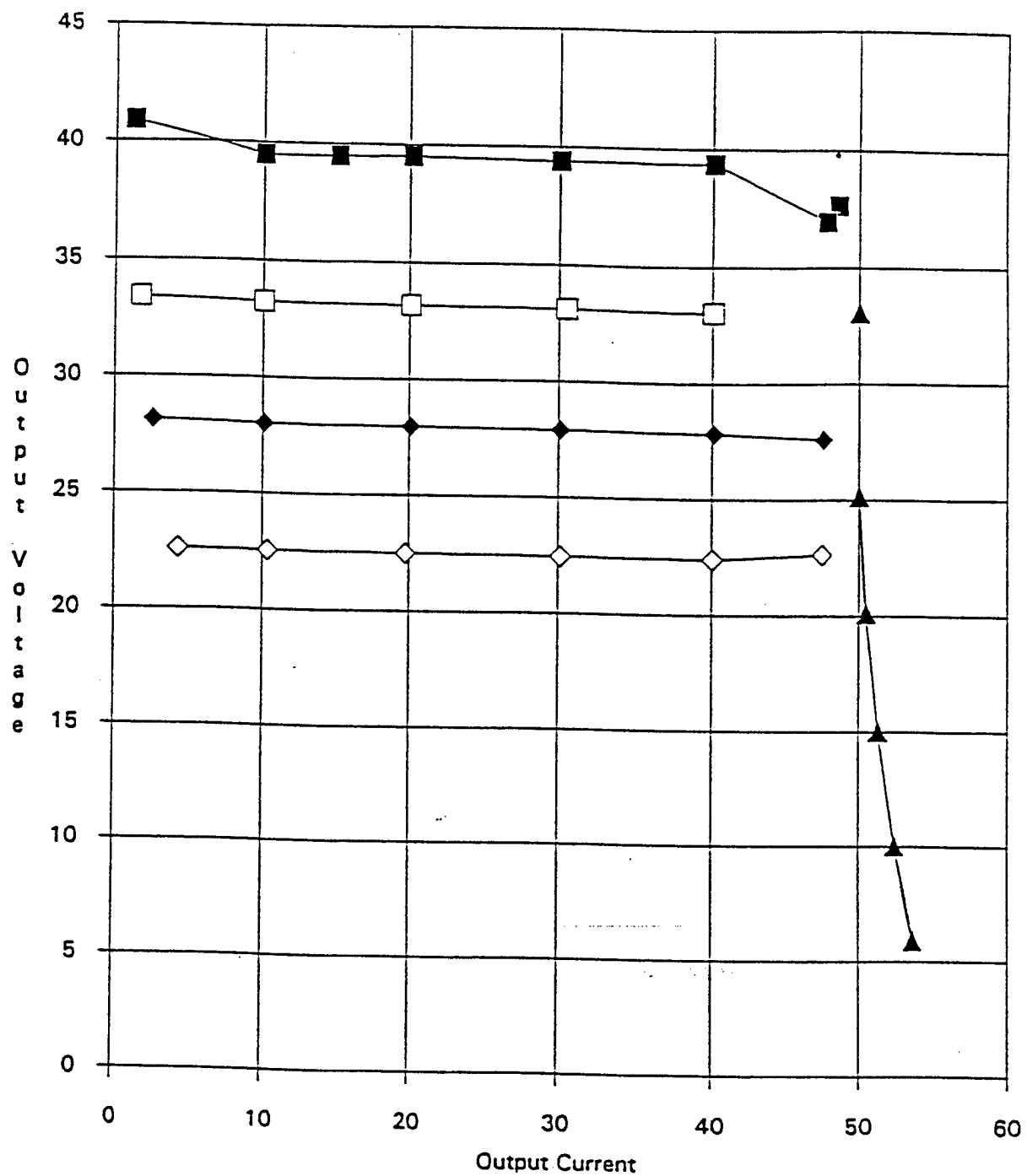
basis of the continuous buck converter, and while the operation remains continuous the control law for the output, V_o , is upheld.

The control circuits monitor the output voltage and current and receive input references from the controller module. The references set the output voltage and current maximums. The control circuits provide the methods to regulate the output voltage or current by comparing these output signals to the input references and then changing the duty cycle of the switching logic that controls the power devices in the half-bridge converter. This technique is known as Pulse Width Modulation (PWM).

The charger control circuits also contain protection circuitry which will turn off the charger if the control circuits cannot control the output voltage or current as commanded. The BIT circuitry can also command a shut-down, as described later. The limits for shut-down are done under hardware control such that a failure in the software cannot cause damage to the battery or the battery charger.

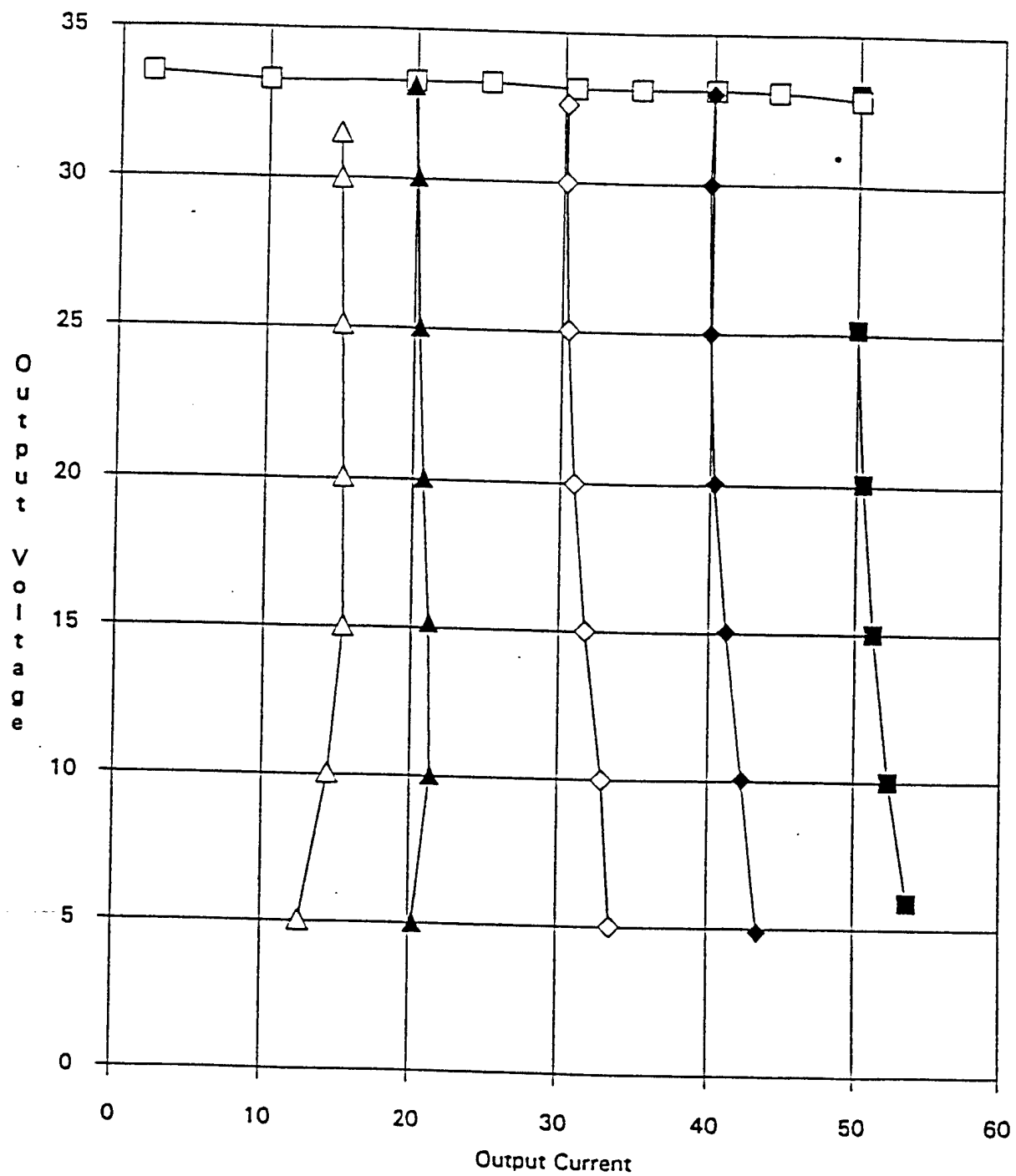
When the charger is operating in the voltage control mode (constant potential) the charger will regulate the output voltage to the level requested by the controller. This is accomplished by controlling the duty cycle. If the charger is in the constant current mode, the charger will regulate the output current to the current requested by the controller. This, too, is accomplished by controlling the duty cycle. These two modes of operation are shown in figures 5-3 and 5-4. Figure 5-3 shows the constant potential mode of operation. This graph shows four different conditions where the output voltage is programmed to regulate between 22 and 38 volts. In each case the output current is varied between zero and 60 Amps. The current maximum for this test was set at 50 Amps. As can be seen, the output voltage remained very constant for varying load conditions in the constant potential mode. This is true until the current reached the maximum (50A), at which time the voltage drops and thus protects the charger as designed.

Figure 5-4 shows the constant current mode of operation. This graph shows five different current curves ranging from 8 Amps to 50 Amps. For all of these conditions a resistor load was varied in order to force the voltage at the output terminals to change. In each case the output voltage maximum was set to 33V. As can be seen from the graph the load regulation is not as precise as the voltage regulation. It is, however, adequate for battery charging because the actual current can be off by several amps and the charging can still be completed in the 60 minute time frame. The maximum voltage however is much more critical for the battery and this function is very tightly regulated even in the constant current mode.



CONSTANT POTENTIAL MODE

FIGURE 5-3



CONSTANT CURRENT MODE

FIGURE 5-4

Both graphs depict the wide operating range of the charger which allows usage for many sizes of batteries. The control circuits provide the PWM signals to the base drive circuits that are used to drive the power devices in the half-bridge converter. The power devices used in this charger are power transistors with low losses. These transistors were selected because of their high gain capabilities over temperature.

The auxiliary regulator converts the ac input voltage after the EMI filters to three dc voltages at low power levels to provide bias power for the controller module and the control and BIT circuits in the charger module. The voltages used are; an unregulated voltage of approximately 26 volts and two regulated voltages at +20 and +5 volts.

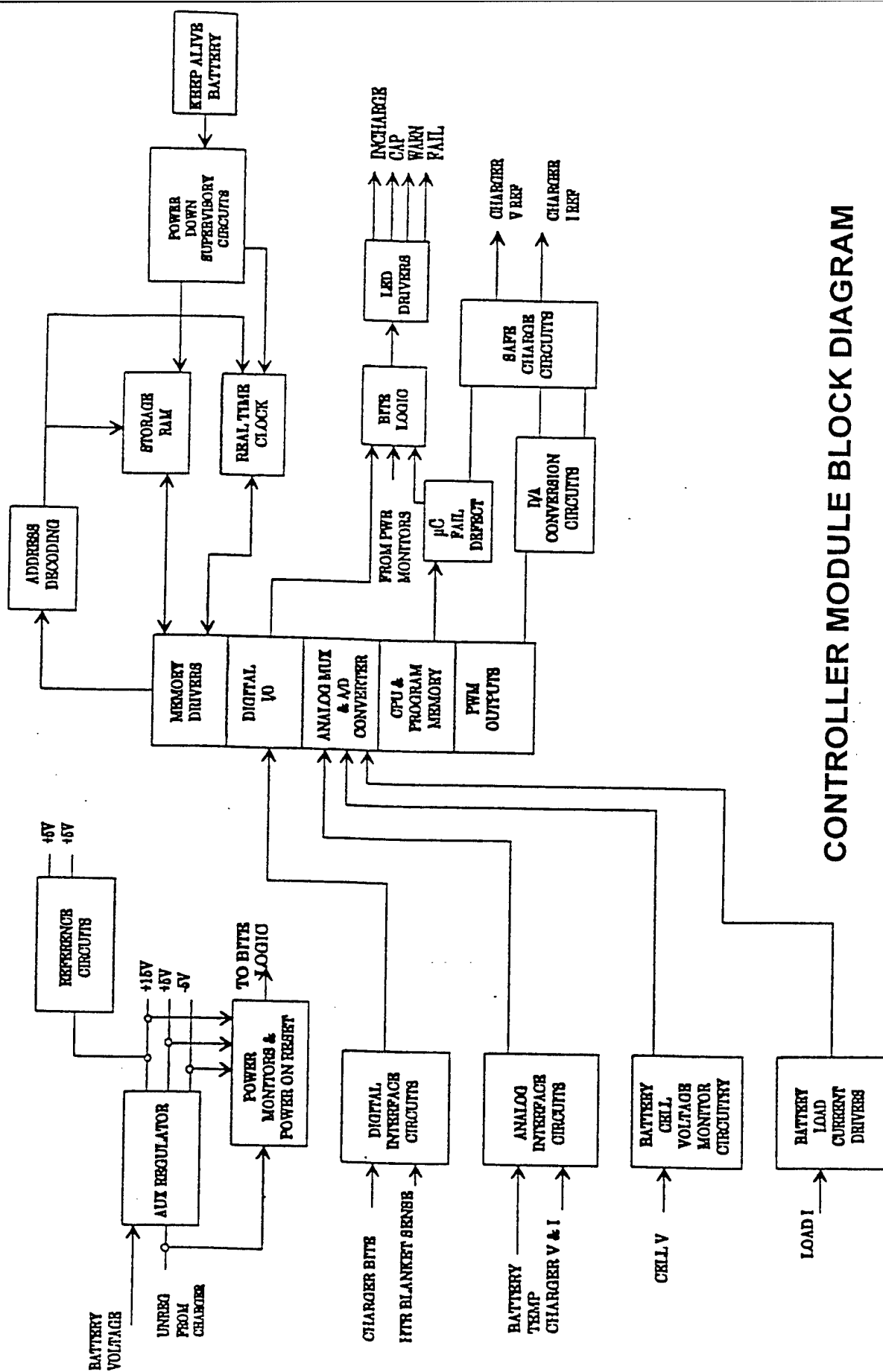
The BIT circuits in the charger monitor the output voltage, output current and the input references and indicate status to the controller. If the charger shuts down, a "charger-off" signal is sent to the controller. The controller can then respond appropriately. This function is described in more detail in both the controller and software sections (5.1.2 and 5.1.3).

5.1.2 Controller Design

The controller module is microprocessor controlled and provides the circuitry and software to control the basic operation for charging the battery, along with the battery system Built in Test capability.

Figure 5-5 is a block diagram of the controller module. The input power for the controller module is taken from either the converter module while powered under aircraft power or the battery for backup operating modes. The unregulated input power is refined to provide three regulated voltages (+15, +5 and -5 volts) for the controller. Separate regulators are used to provide redundancy so that a failure in the controller will not cause a failure in the charger and vis-versa. The +15 volt output also supplies power for two internal references of +5 volts used for the A to D and to set up references for BIT tolerance levels. Each of the unregulated and regulated voltages is monitored by the power monitor circuits. The unregulated voltage from the charger module is representative of the ac input voltage. The power monitor circuits, when ac and dc input power is within operating limits, will issue a power on reset to start the system software which begins the charging sequence.

Digital inputs are processed individually and are made up from the charger BIT inputs and the heater blanket sense circuits. The charger BIT inputs provide information on charger status. If the charger is shut down because of a fault the charger BIT will also indicate if the fault is output voltage or current induced. The heater blanket sense circuit senses the battery heater blanket operation.



CONTROLLER MODULE BLOCK DIAGRAM

FIGURE 5-5

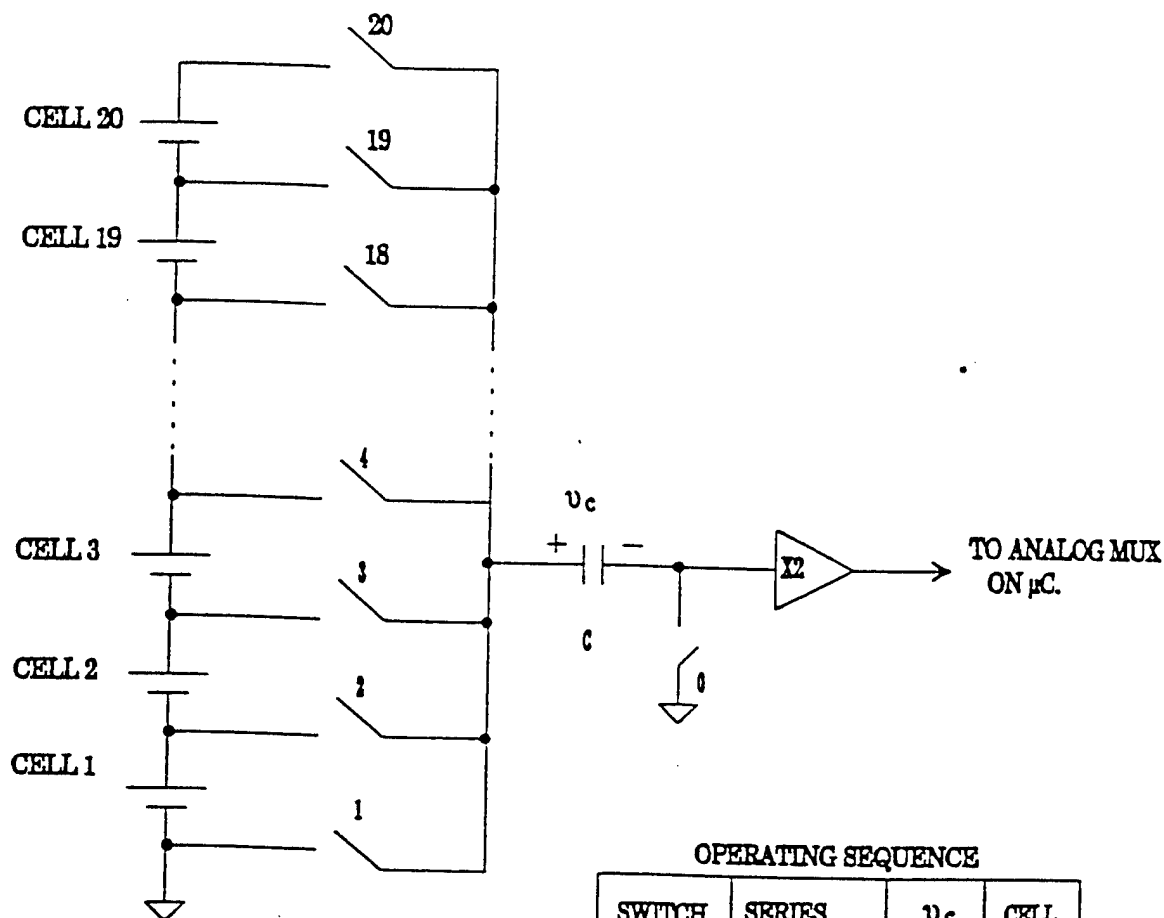
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There are many analog inputs to the controller module and they are sensed by three different means. The battery temperature and the charger output voltage and current are very straightforward and require simple interface circuits. Once these signals are captured and scaled they are input into the analog multiplexer on the microcontroller.

The battery cell voltages are also monitored as an analog signal. This cell voltage monitor circuitry is more complicated in its operation. Figure 5-6 is a simplified schematic of the circuit. In order to maintain good accuracy in measuring the differential voltages, a switched capacitor type network was utilized. The operating sequence for the circuit can be followed by the table that accompanies the simplified schematic on Figure 5-6. The software controls the operation of the switches in this circuit. During the operation sequence the capacitor C is first discharged by turning both switch 0 and switch 1 on. Next, switches 0 and 1 are turned off and 2 is turned on. At this instant the voltage at the input of the amplifier is equal to the first cell voltage and the system makes the measurement. After the measurement is made switch 0 is turned on and the capacitor charges to the level of the first cell voltage. The next step is the same as before, 0 and 2 are turned off and 3 is turned on. At this point the voltage on the capacitor is equal to the first cell voltage and the circuit is connected to the second cell. Therefore the voltage on the input to the amplifier is equal to the sum of the first two cells minus the first cell, that is to say the value of the second cell. Once again a measurement is made, switch 0 is closed and the capacitor C is now charged to the value of cell 1 plus cell 2. This process repeats until the top of the battery cell string and once cell 20 is measured the capacitor is then shorted out by switches 0 and 1 so the whole sequence can start again. This circuit provides an accurate account of the cell voltages with a better than 4% accuracy level per cell. Table 5-1 indicates the test data for the cell voltage accuracy of the circuit. This table shows the worst case readings, and what cell provided those readings for battery voltages between 18 and 32 volts.

The load current measurements are complex in nature. This circuit only measures one current but it is designed to have high accuracy from 0.1 to 300 Amps. Figure 5-7 is a simplified schematic of the battery load current circuit. This circuit only operates if the charger is shut down. When the charger is operational, it can provide the load current (up to 50A) to the system. The circuit checks the current once per second as shown in the timing diagram in Figure 5-7. The event only takes 2 milliseconds to measure the current out of the battery.

The circuit is a full bridge type drive on a dc current transformer which is located within the battery. The drive circuitry saturates the transformer in the same direction as the dc current flow when switch Q2 and Q3 are turned on. When the 1-second interval occurs, which is provided by an interrupt from the real time clock, then Q2 and Q3 are turned off and Q1 and Q4



SIMPLIFIED CELL VOLTAGE MONITOR CIRCUIT

FIGURE 5-6

J8601DEW

OPERATING SEQUENCE

SWITCH	SERIES SWITCH ON	v_c (V)	CELL #
ON	1	0V	.
OFF	2	0	1
ON	2	1.2	.
OFF	3	1.2	2
ON	3	2.4	.
OFF	4	2.4	3
ON	4	3.6	.
.	.	.	.
.	.	.	.
.	.	.	.
OFF	18	20.4	18
ON	18	21.6	.
OFF	19	21.6	19
ON	19	22.8	.
OFF	20	22.8	20
ON	20	24.0	.

TABLE 5-1

CELL VOLTAGE ACCURACY TEST

TEST "V"	CELL "V"	A/D CNT	MEAS. "V"	LOWEST "V" CELL #	HIGH "V" CELL #	%ERROR
18.000	0.900	89.000	0.873	1		3.050
18.000	0.900	95.000	0.931		19,20	-3.486
20.000	1.000	99.000	0.971	1		2.941
20.000	1.000	105.000	1.029		7,20	-2.941
22.000	1.100	109.000	1.069	1		2.852
22.000	1.100	115.000	1.127		7,20	-2.496
24.000	1.200	119.000	1.167	1		2.778
24.000	1.200	126.000	1.235		7,20	-2.941
26.000	1.300	129.000	1.265	1		2.715
26.000	1.300	136.000	1.333		7,20	-2.564
28.000	1.400	139.000	1.363	1		2.661
28.000	1.400	147.000	1.441		7	-2.941
30.000	1.500	149.000	1.461	1		2.614
30.000	1.500	157.000	1.539		7,14	-2.614
32.000	1.600	158.000	1.549	1		3.186
32.000	1.600	167.000	1.637		7,14,20	-2.328



FIGURE 5-7

turned on. This forces the dc transformer out of saturation and the current that flows thru the resistor string below Q4 is the transformed current from the battery. This current flows thru a weighted resistor string to provide three levels of voltages. The first resistor R1, provides for low ranges of currents up to 3 Amps. At which time the voltage drop across R1 exceeds the diode drop and the diode conducts. R2 then provides the medium range from 3 to 30 Amps of current.

It too has a diode in parallel that conducts for currents greater than 30 Amps. Then the final range that will provide 30 to 300 Amps is provided by R3. Each of these resistors are monitored with a differential amplifier that provides a gain of 10. This output signal is then sent to the analog input of the microcontroller and the reading is taken and stored. The software stores all three readings every second and determines from the values of the readings which range is appropriate. Once this is done it calculates the proper battery current and stores it in memory. By making the measurement on a 1-second interval, the current can be integrated over time to provide the appropriate amp-hours to determine the battery capacity. Table 5-2 shows the battery load current accuracy data measured from the charger controller. As can be seen from the uncorrected measurements, the circuit has an offset error. This is corrected easily in software by subtracting the offset from the measured voltage and the corrected accuracy is within 5% for the entire range of currents.

The heart of the controller module is a microcontroller (uC). The microcontroller used is the Intel 87C196KC. This microcontroller contains not only the main Central Processing Unit (CPU), it also has built in to it the following:

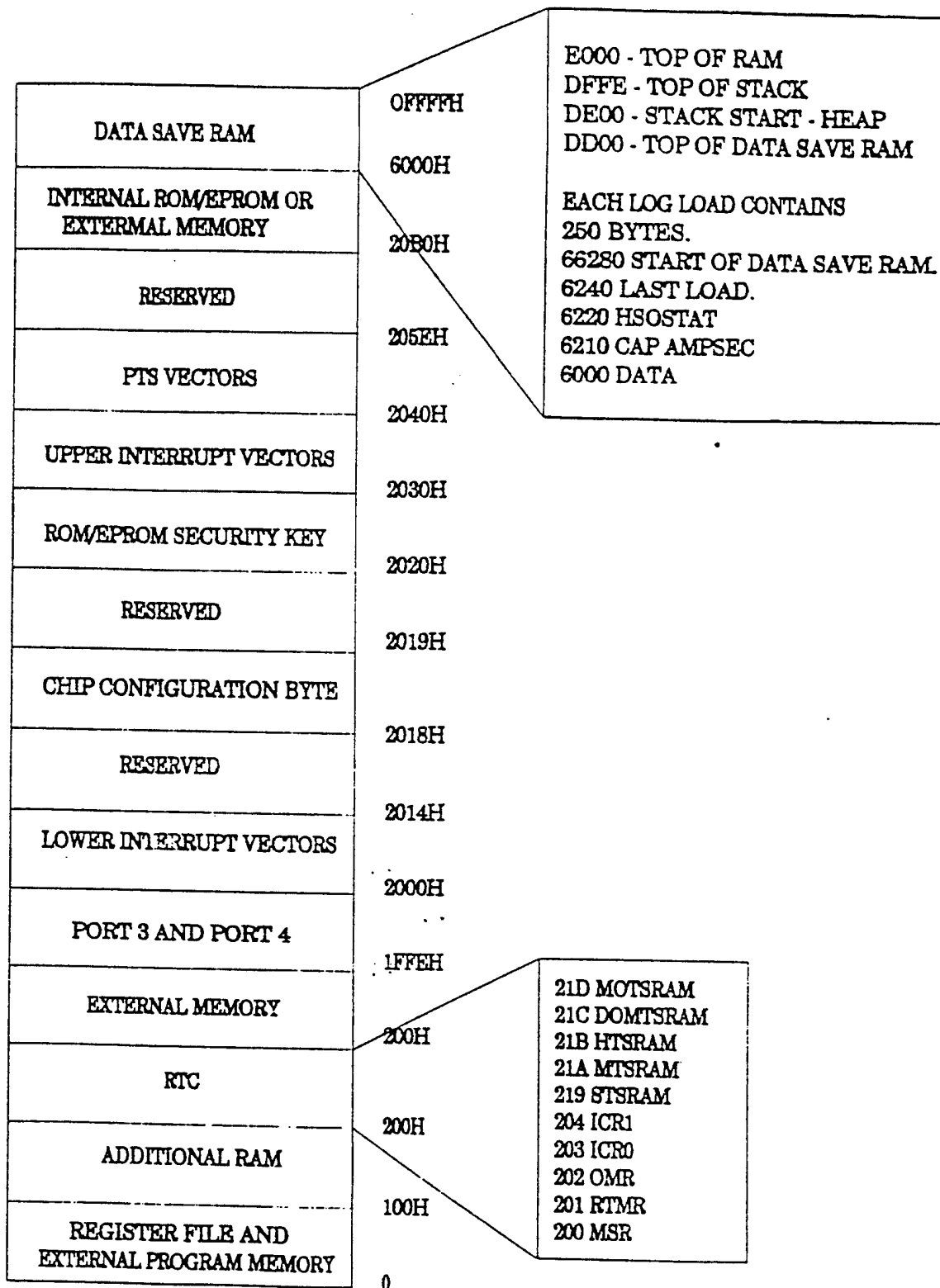
- 1) Memory Drivers - This function provides address and data lines to provide control for external memory elements.
- 2) Digital inputs and Outputs - There are two 8-bit ports used for digital inputs and outputs.
- 3) Analog Multiplexer and A/D Converter - There is an eight channel analog multiplexer with a sample and hold input to a 10-bit A/D converter.
- 4) 512 Bytes RAM - The internal RAM is used for special function registers, and scratch pad memory.
- 5) 16K Bytes Program EPROM - The EPROM space contains the operating software. This design utilizes about half of the available memory.
- 6) PWM outputs - These outputs are used with a simple filter circuit to provide analog outputs to control the charger.

Figure 5-8 contains a memory map which describes the location in memory for each of the functions.

Table 5-2

BATTERY LOAD ACCURACY CHECK

"I" SHUNT	RANGE	ANALOG VOLTAGE	MEASURED "I"	% ACCURACY	CORRECTED VOLTAGE	CORRECTED CURRENT	CORRECTED ACCURACY
0.158	L	0.631	0.380	140.583	0.262	0.158	-0.107
0.282	L	0.860	0.618	83.714	0.491	0.296	4.888
0.62	L	1.434	0.864	39.332	1.065	0.642	3.478
1.08	L	2.190	1.319	22.155	1.821	1.097	1.573
2.05	L	3.765	2.268	10.638	3.396	2.046	-0.206
3.01	L	5.270	3.175	5.472	4.901	2.952	-1.913
4.04	M	0.708	4.265	5.571	0.671	4.043	0.069
6.02	M	1.042	6.277	4.271	1.005	6.055	0.578
8.14	M	1.392	8.386	3.016	1.355	8.163	0.286
10.03	M	1.707	10.283	2.524	1.670	10.061	0.308
12.04	M	2.041	12.295	2.119	2.004	12.073	0.273
14.05	M	2.374	14.301	1.788	2.337	14.079	0.206
16.04	M	2.705	16.295	1.591	2.668	16.073	0.205
18.03	M	3.033	18.271	1.337	2.996	18.049	0.104
20.02	M	3.362	20.253	1.164	3.325	20.031	0.054
25.02	M	4.191	25.247	0.807	4.154	25.025	0.019
30.06	H	0.509	30.663	2.005	0.505	30.440	1.265
35.01	H	0.589	35.482	1.348	0.585	35.260	0.713
40.02	H	0.669	40.301	0.703	0.665	40.079	0.147
45.03	H	0.750	45.181	0.335	0.746	44.958	-0.159
50.02	H	0.832	50.120	0.201	0.828	49.898	-0.244
74.1	H	1.275	76.807	3.653	1.271	76.585	3.353
101.7	H	1.745	105.120	3.363	1.741	104.898	3.145
123.3	H	2.137	128.735	4.408	2.133	128.513	4.228
151.7	H	2.529	152.349	0.428	2.525	152.127	0.282
179.8	H	2.980	179.518	-0.157	2.976	179.296	-0.280
200.9	H	3.314	199.639	-0.628	3.310	199.416	-0.739
227.8	H	3.922	236.265	3.716	3.918	236.043	3.618
252.3	H	4.235	255.120	1.118	4.231	254.898	1.030
278.2	H	4.588	276.386	-0.652	4.584	276.163	-0.732
305.3	H	5.000	301.205	-1.341	4.996	300.983	-1.414



80C 196KC MEMORY MAP

FIGURE 5-8

On the output side of the block diagram we have address decoding circuits which decode the address lines from the uC to drive the external memory. External memory consists of the Data Storage RAM and the Real-Time Clock (RTC). The RTC is a memory mapped device that provides real-time information that is used to identify the date and time any events occur. Each of these two elements need to have battery back up to hold the information when disconnected from the main aircraft battery. There are power down circuits and a sealed lithium 5 A-hr primary battery to provide the required back up power and control.

The digital output from the uC along with power monitor circuit outputs are sensed by the BIT logic. The BIT logic takes these inputs and provides the hardware logic to supply the four BIT signals to the aircraft as described in the SCD. The logic circuit outputs are then provided to LED drivers so users need only connect an LED to the output to obtain the BIT light function.

The uC has internal reset capabilities so if the software "gets lost," the uC will automatically reset itself and resume normal operation. If there is a problem where the processor is continually resetting itself, then the uC fail detect circuitry will recognize this and provide input to the BIT logic and the Safe Charge Circuits.

The Safe Charge Circuits provide the analog output drive to the charger module. If the uC is operating properly its PWM outputs provide inputs to a D to A conversion circuit that converts the PWM output to an analog voltage. This voltage is sent thru an analog switch to the charger module. If the uC is upset, the uC fail detection circuitry will force the safe charge circuits to provide a hardware voltage and current reference to safely charge the battery. These signals are buffered and sent via the analog switch circuit.

While operating in this fail safe mode, the charger operates in the constant potential region and the output voltage and current are fixed at a level that will slowly charge the battery without the threat of battery damage even for prolonged charge periods.

5.1.3 Software Design

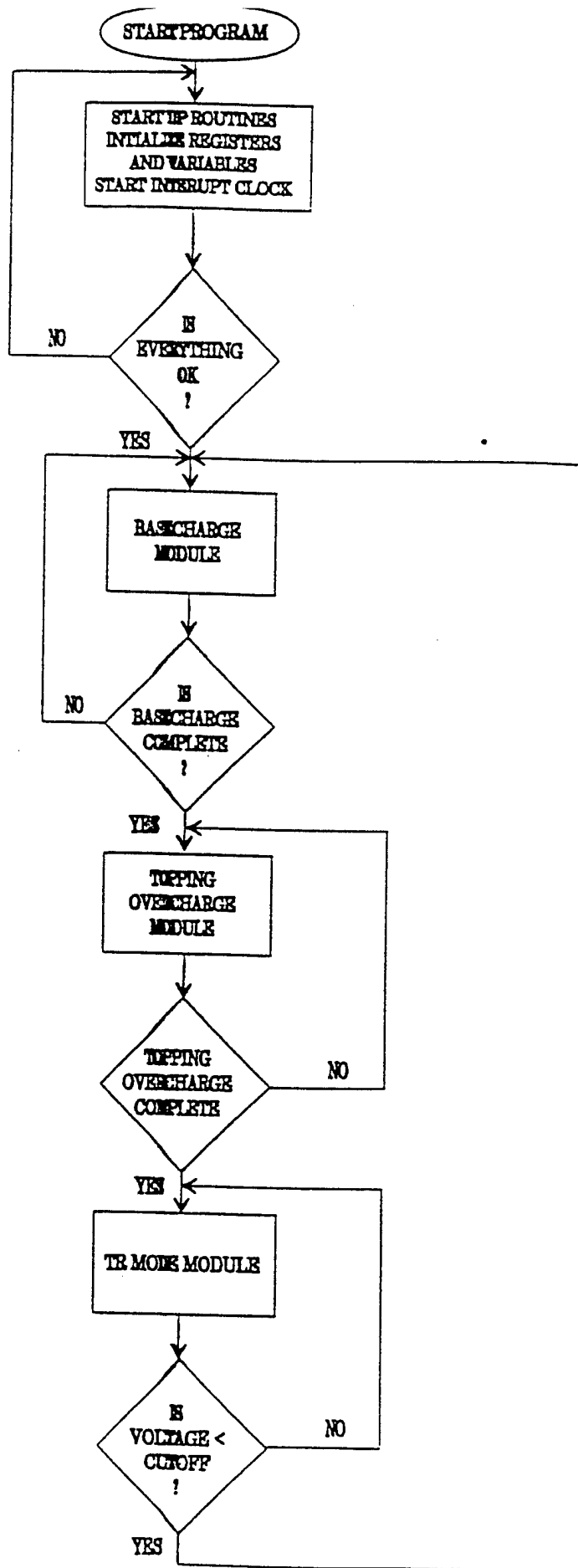
The charger/controller operates under software control. The software provides the basic control algorithm for charging the battery and it also performs the battery system BIT function. The software is partitioned into two operating modes. The main loop provides the control for charging the battery and the interrupt structure provides updates and tests for the BIT functions.

Figure 5-9 shows the flow chart for the main loop of the software. The program begins execution at the start after any microcontroller reset. A reset can be initiated by any one of the

MAIN LOOP PROGRAM FLOW

FIGURE 5-9

JB509.DRW



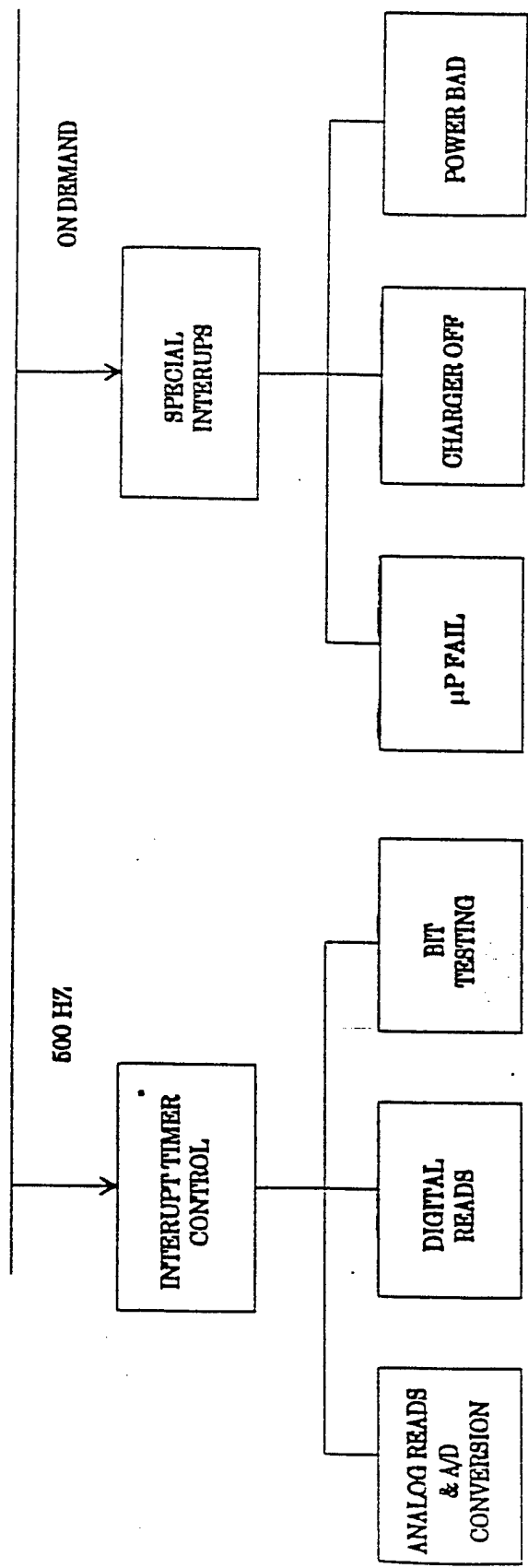
following events; AC power application, aircraft battery connect and uC upset. At initialization the program goes through a start up sequence which initializes variables, sets up all of the special function registers, and starts the interrupt clock. This initialization takes about 3 seconds to check out the entire system. Once the system checks out as functional, the charger commands a constant current base charge mode of operation (approximately 40A). The charger continues to provide the base charge until the battery voltage reaches a temperature compensated cut off voltage or if the battery voltage rolls over and changes to a negative slope. The charger will then command the overcharge constant current (approximately 12.5A). This current is commanded and controlled until the battery voltage reaches another temperature compensated cut off voltage or if the battery voltage rolls over and changes to a negative slope. The next mode of operation is the constant potential mode. During this mode the charger provides a constant voltage output to the battery of approximately 27.5V. The charger remains in this mode of operation until the battery voltage falls to below 23V at which time the base charge mode will resume.

At any time in the operation of the charger if the input power is cycled, any fault, or any reset occurs, then the system will respond accordingly as described below.

Figure 5-10 shows the interrupt structure for the charger/controller. The I/O control and BIT functions operate under interrupt control. The interrupts are time multiplexed with the main loop software. Internal to the microcontroller is a timer interrupt routine that automatically halts execution of the main loop software at a programmable rate. The rate used in the charger/controller is 500Hz. This means that every 2 milliseconds the interrupt timer stops the main loop software and executes the interrupt software. The interrupt software also contains a timer which determines which input port to read or what test to perform. There are 50 different steps in the software timer so that each test and each input read is done 10 times per second. All of the inputs both analog and digital are read and checked to make sure they are within proper operating limits as part of this routine.

Special interrupts for shut down conditions are part of the interrupt routines. These interrupts must be acted upon immediately and are therefore available on demand. Any time there is a charger shutdown or the power to the charger/controller is out of tolerance, the microcontroller responds immediately. The uC then takes appropriate action to protect the battery system, store the failure or shutdown in memory, and report the condition via one of the BIT indications.

If the condition persists, the charger/controller will remain in this mode. If the condition corrects itself then the charger/controller will automatically restart and resume operation.



INTERRUPT STRUCTURE

FIGURE 5-10

JBA10.DRW

At any operation mode change or for any fault or warning that may occur, the software stores a complete set of data in nonvolatile memory. Figure 5-11 shows the data that are stored in memory for any of the above occurrences. The date, time, and operation mode are stored. If there was a failure, the failure type is also recorded. Then the battery data are stored. These data include battery temperature, overall battery voltage and each individual cell voltage. The charge removed from the battery is stored as amp-seconds and the internal "keep-alive" battery voltage is recorded. Charger information that is stored includes the commanded current and voltage along with the actual current. Several digital signals are stored which are used to further isolate faults for failure conditions.

5.2 Mechanical Design

5.2.1 Packaging Concept

The 4-521-01 Maintenance Free Battery charger was developed as a modification of an existing ELDEC battery charger P/N 4-254. The objective was to provide a quick-turn around development for system verification testing and minimize risk by using a "proven unit." The resulting product was essentially an ELDEC 4-254 with a microprocessor based controller and interface section added to the rear; and retaining the power section of a proven design (see Figure 5-12 "4-521-01 Mechanical Layout").

5.2.2 Chassis Layout

Reference Figure 5-12; which shows an exploded view of the unit. The ELDEC 4-254 (from which the 4-521-01 was derived) is sized to a 6 MCU ARINC format. The 6 MCU ARINC format is 7.5 inches wide, 7.6 inches high and 12.5 inches long. The 4-521-01 is packaged by adding a 1.5 inch extension to the ELDEC 4-254 charger chassis making the total length 14 inches.

The package is formed by using straight fin vertical heatsink extrusions as sides and joining these with sheet metal top, bottom and front. The top and bottom are flat plates which are perforated to allow free convection air flow.

The input filtering capacitors and inductors are mounted to the backside of the front panel. The main power devices (drive and power transformers, inductors, rectifiers and transistors) are mounted to the heatsink sides. The rear of the chassis is a machined plate which serves as a heatsink and thermal conduction path for the controller/interface section.

Machined brackets are added to the front and rear of the unit, allowing it to be mounted at the unit bottom surface.



LOGLOAD SCREEN

DATE: 11/8/89 TIME: 7:49:40
BASE CHARGE NO FAILURES

BATTERY DATA

TEMPERATURE: 24.0 °C VOLTAGE: 21.20

CELL VOLTAGES

0:	1.06	1:	1.07	2:	1.05	3:	1.06	4:	1.06
5:	1.07	6:	1.05	7:	1.07	8:	1.07	9:	1.07
10:	1.06	11:	1.05	12:	1.05	13:	1.06	14:	1.06
15:	1.06	16:	1.05	17:	1.06	18:	1.06	19:	1.06

AMP SECONDS REMOVED FROM BATTERY: 115,200
KEEP ALIVE BATTERY VOLTAGE : 3.67

CHARGER INFO

COMMANDED OUTPUT I: 50.73 V: 33.51
ACTUAL CHARGER OUTPUT I: 50.63

PORT 1 STATES

IERR	VERR	CHRGCON	CHRGGOOD	CHRGROC	RMSHTDN	CHGRCNTL	INTRBLKON
1	1	0	1	1	0	0	1

DATA STORED IN MEMORY

FIGURE 5-11

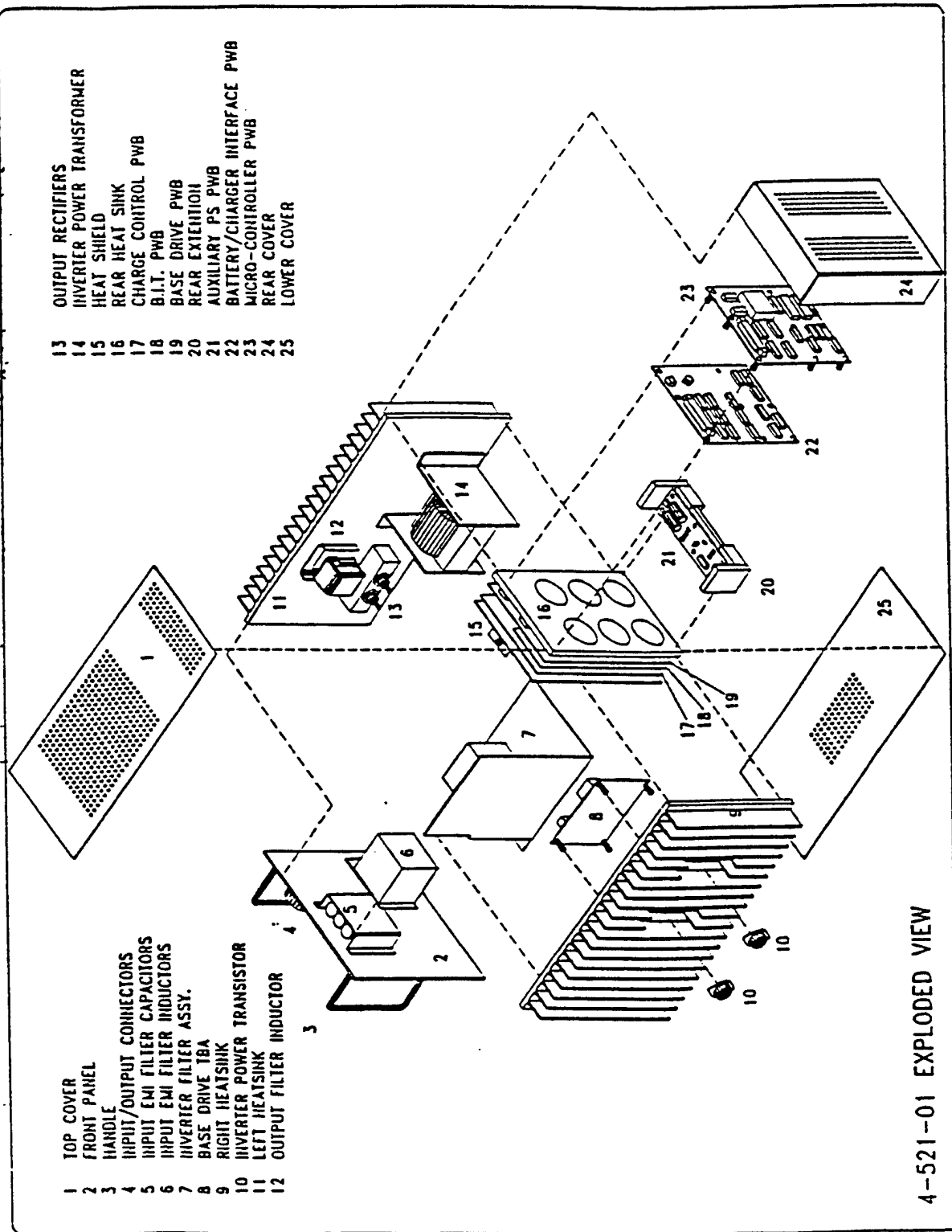


FIGURE 5-12

5.2.3 Major Sub-Sections

The 4-521-01 consists of the charger power section (from the existing ELDEC 4-254 charger) and a microprocessor based controller/interface section which is mounted to the rear of the unit in a "dog house" configuration.

5.2.3.1 Charger Section - Mechanical Design

The charger section is laid out for the primary current loop to move counter clockwise (when viewed from the top) thru the unit beginning with the input connector J1 and ending at the output terminal block, TB1.

All inputs and outputs of the 4-521-01 go thru the front panel. The primary current loop begins with the input filter capacitors and inductors mounted to the front panel.

From the input filter section primary current loop moves to the right side heatsink which mounts the inverter input rectifiers, the auxiliary power supply, base drive transformers and inverter power transformers.

Near the rear of the unit is a heat shield which prevents heat from radiating to the charger circuit boards mounted directly behind it.

On the left side heatsink is mounted the main power transformer, the output filter inductor and output rectifiers.

The microprocessor controlled levels of direct voltage and current necessary to charge the battery pass thru the output rectifiers and terminate at the output terminal studs of the terminal block TB1 on the front panel.

5.2.3.2 Controller Section - Mechanical Design

In the rear 1.5 inches of the unit, in the "dog house" is the sensing and control circuitry added to the 4-254 to derive a 4-521-01. The circuitry includes a battery to charger interface circuit board, a microprocessor circuit board and an auxiliary power supply.

The interface and processor boards are vertically mounted in parallel on standoffs. The auxiliary power supply board is horizontally mounted at the bottom of the "dog house" section.

5.2.3.3 Interconnect

Due to the high currents involved and the relative few numbers of required connections, the 4-251-01 is interconnected by hard wire and interconnect harnesses. Mass termination and flexible circuitry are not used.

In the rear of the unit; pin and socket connections are used to join charger control board to the base drive circuit board and to join the charger interface board to the microcontroller board. The connection is affected when the boards are "sandwiched" together in their mounted configuration.

5.2.3.4 Circuit Card Assemblies

Circuit card assemblies are two sided and multilayer types designed per the requirements of Mil-Std-275. The circuit boards are manufactured per Mil-Std-55110 and assembled per Mil-P-28809. The boards are fabricated from material per Mil-P-13949 type FR4. Circuit card assemblies are conformal coated per Mil-I-46058 type XY "Parylene." Circuit board terminations are made with MS55302 connectors or solder terminated.

All circuit card assemblies are stand-off mounted. The modal frequencies of vibration for each circuit card assembly have been analyzed to verify the necessary rigidity to minimize deflection and solder joint stress.

5.2.4 Structural Design

ELDEC has a substantial background of experience with the shock and vibration requirements of aerospace electronics. ELDEC currently provides power supplies, battery chargers and TR units for many Boeing, General Dynamics, and McDonnell Douglas military aircraft.

The chassis pieces are joined with large overlap sheet metal interfaces and tight screw spacing. This provides for efficient joints which meet the structural requirements (shock, vibration, acceleration, handling, etc.) of the unit for its testing, operating, handling and manufacturing environments.

The structural joints have been individually analyzed and custom designed for each application. The modal frequencies of the unit have been tailored to minimize component, fastener and solder joint exposure to transmitted levels of vibration and shock.

The ELDEC 4-254 charger (from which the 4-521-01 was developed) was qualified to a random vibration level of 9.9 G's RMS (3 hours per axis).

5.2.5 Thermal Design

5.2.5.1 Thermal Design Concept/Layout

The 4-521-01 charger/controller is designed for continuous operation in a free convection cooling environment. The left and right side chassis walls have vertical straight-finned heatsinks. The major power dissipating components are mounted to these heatsinks which provide the primary cooling interface for the charger/controller. Internally, the unit is cooled by the bottom to top draw-thru natural convection provided by vent holes located in the top and bottom of the unit (see Figure 5-12 Mechanical Layout).

5.2.5.2 Power Sources

The main power dissipating components in the 4-521-01 are approximately as follows:

Item	Description	Power Diss.
13	Rectifier	48 Watts
14	Power Transformer	65 Watts
21	20V Regulator	3 Watts
10	Transistor Q2	30 Watts
10	Transistor Q1	30 Watts
7	Auxiliary Transformer	3 Watts
7	Input Bridge	15 Watts

The item number corresponds to the item on Figure 5-12.

5.2.5.3 Thermal Design Capabilities

Normal Operating

The 4-521-01 is designed to operate between -55°C and 71°C (@ 40 amps continuous output).

Temperature-Altitude

The high temperature altitude operating capability of the 4-521-01 is as follows:

<u>Altitude</u>	<u>Temperature</u>
Sea Level	71°C
10,000 Ft.	64°C
20,000 Ft.	53°C
30,000 Ft.	41°C
40,000 Ft.	25°C
50,000 Ft.	6°C

5.2.5.4 Thermal Design Similarity

The 4-521-01 thermal design is based on the proven 4-254 which was qualified for operating between -55°C and 71°C. The 4-254 was qualified at 38 amps continuous operation in an 71°C environment without cooling air (and the bottom air holes blocked off).

With the similarity of material parts and processes between the 4-254 and its derivative it is reasonable to expect comparable thermal performance. See the "Safety of Flight Testing" section for the confirmation test data.

5.2.6 Drawing Package

The drawing package for the charger will be submitted under separate cover due to the size and nature of the package. This deliverable will be an ELDEC Level 2 compatible drawing package. Figure 5-13 is the drawing tree for the charger which describes the drawing package breakdown. The items on the left side of the drawing tree represent the drawings that make up the base 4-254

unit from which the 4-521 charger is made. The center section of the drawing tree shows the modification drawings which are used to modify the 4-254 drawings in order to accommodate the new circuits and hardware for the 4-521. The drawings required for the additional hardware to build the 4-521 charger.

6.0 Safety of Flight Testing

Safety of Flight testing was done independently on the battery and the charger/controller. Compatibility testing was done as a system and is described in the next section.

6.1 Battery Testing

The safety of flight testing applicable to the batteries is listed below:

Humidity	Similarity
Salt/Fog	Similarity
Vibration	Test
Temperature Shock	Test
Electromagnetic Interference	Similarity
Performance Testing	Similarity

6.1.1 Similarity Data

Conditions that are qualified by similarity on Eagle-Picher part numbers 18213 and 18214 are based on Eagle-Picher part number EPI-18164. This is a 20 cell 36 ampere hour nickel-cadmium aircraft starting battery designed for the Bell 214ST helicopter. The batteries will meet all requirements based on the same basic design and development principles used for this battery.

Eagle-Picher part numbers 18216 and 18192 were qualified by similarity based on EPI-18213. These batteries incorporate the same basic design and manufacturing principles, and are subjected to virtually all the same operating circumstances. Based on these conditions, EPI part nos. 18147 and 18192 will meet all requirements.

6.1.2 Vibration Testing

6.1.2.1 Purpose

Vibration testing was performed on all four batteries to ensure they are constructed to withstand dynamic vibrational stresses and that performance degradation or malfunction will not be produced by the operating environment.



FIGURE 5-13

6.1.2.2 Conditions

Eagle-Picher performed sine sweep and random vibration testing on each battery per MIL-STD-810C. The batteries were prepared and tested under simulated operating conditions; discharge representing engine start, and charging representing flight conditions. All units were continuously monitored throughout the vibration test procedures.

6.1.2.3 Results

No operational faults were detected on EPI part numbers 18213, 18214, 18216 and 18192 during the sine sweep vibration testing or on the random vibration testing.

6.1.2.4 Vibration Testing Conclusions

With the prescribed vibration levels, structural integrity and workmanship have been confirmed. Where these units are expected to be mounted in the aircraft, we believe that the separation from normal vibration generation sources is sufficient and that the batteries, having successfully withstood the vibration testing, will meet the need of the program systems evaluation.

6.1.3 Temperature Shock Testing

6.1.3.1 Purpose

Temperature shock testing is conducted to determine the effects on the batteries to sudden changes in temperature and operating environments.

6.1.3.2 Conditions

Temperature shock testing was conducted on the EPI-18213 and EPI-18214 batteries. The units were prepared and tested in accordance with MIL-STD-810, Method 503.1, Procedure I.

6.1.3.3 Results

At the conclusion of the temperature shock testing, the batteries were returned to the standard ambient conditions and allowed to stabilize. The units were then inspected and tested. The batteries showed no signs of loss to structural integrity and workmanship, and no loss of electrolyte was detected. There was also no significant loss of capacity or performance.

6.1.3.4 Temperature Shock Testing Conclusion

Based on the conditions set forth in MIL-STD-810, Method 503.1, Procedure I, and the successful completion of the testing by the batteries, Eagle-Picher has proven that these batteries will meet the needs of the program systems evaluation.

6.2 Charger/Controller Testing

The safety of flight testing applicable to the charger/controller is listed below:

Humidity	Similarity
Salt/Fog	Similarity
Vibration	Test
Temperature	Test
Electromagnetic Interference	Similarity
Performance testing	Test

6.2.1 Similarity Data

Conditions that are qualified by similarity are based on ELDEC part numbers 4-254 Charger, 4-056 Charger, and 4-153 Converter Assembly (regulated). The 4-254 is a battery charger designed for the Boeing 757, 767 aircraft. The basic design approach is also used on the Embraer AMX aircraft and it is the base unit for the charger/controller. The 4-056 is a battery charger used on the Sikorsky Black Hawk Helicopter. The 4-153 is a regulated 28V converter assembly used by General Dynamics on the Tomahawk missile program. The similarity report for the 4-254 covers the following tests:

Explosive Atmosphere
Sand and Dust
Humidity
Fungus
Salt Spray

The charger/controller will meet these requirements based on the similarity in design and performance with the aforementioned test unit and data.

6.2.2 Vibration Testing

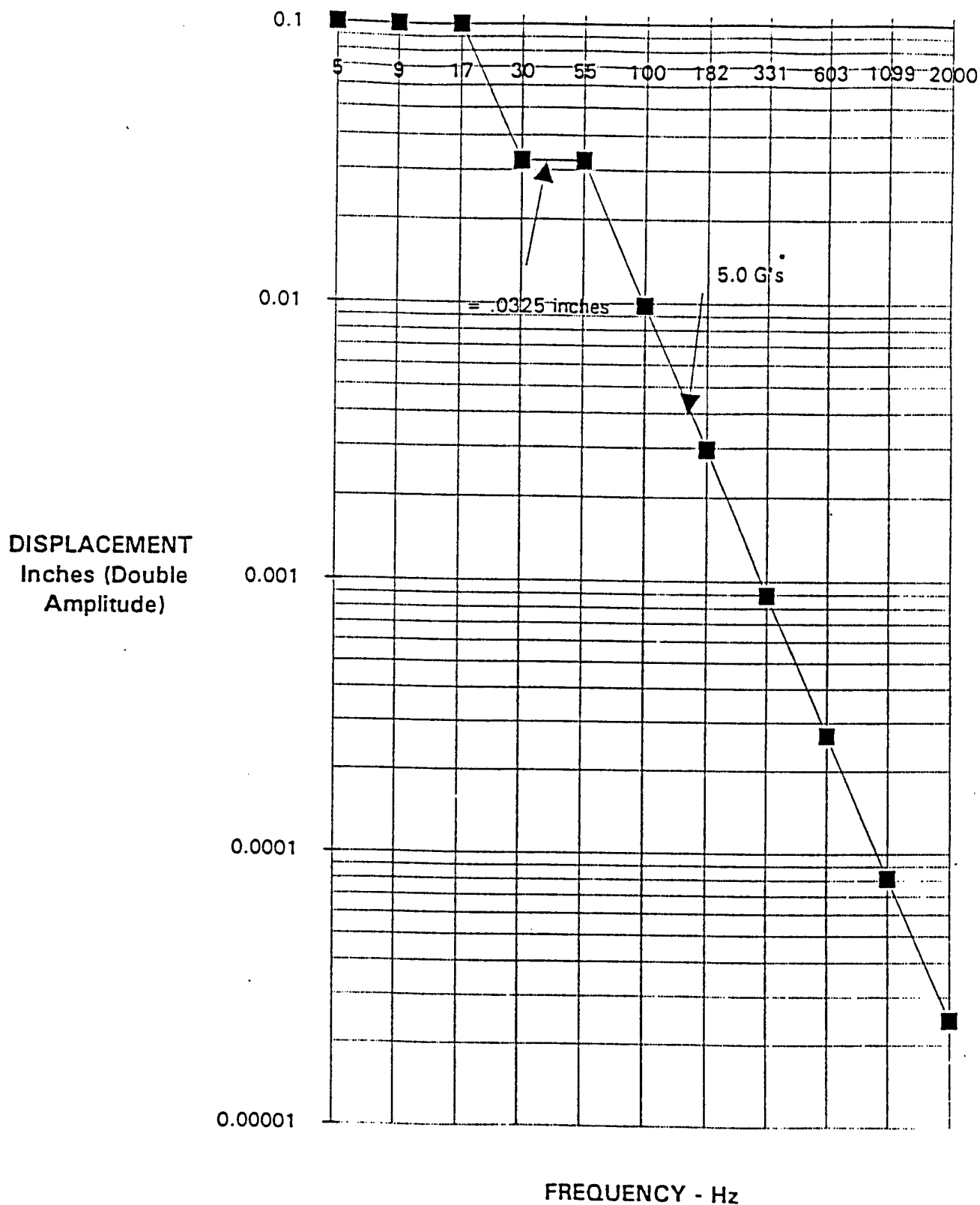
6.2.2.1 Purpose

Vibration "confidence level testing" was performed on a 4-521-01 to verify the unit capability and confirm manufacturing workmanship. Raw data was collected in ELDEC Design and Computation Notebook Number 367 issued to ELDEC Electronic Technician Rick Perrault.

6.2.2.2 Conditions

ELDEC performed a sine sweep and random vibration test per Mil-Std-810C. The unit was powered and output continuously monitored throughout the following vibration test procedure:

- 1) Sine sweep from 5 to 2000Hz at 5 G's maximum (per Figure 6-1 "Sine Sweep Vibration Test Curve") and identify the four most severe responses.



Sine Sweep Vibration Test Curve

Figure 6-1

- 2) Dwell for 30 minutes on each of the resonant responses identified as significant.
- 3) Identify and correct those design elements which exceed the allowable response.
- 4) Perform a random vibration test (per Figure 6-2 "Random Vibration Test Curve") (4.9 G's RMS). The test was run for one hour per axis.¹

6.2.2.3 Results

- 1) No operational faults were detected on the charger/controller unit under test, 4-521-01, SN 00x during the sine sweep vibration testing.
- 2) No operational faults were detected on the charger/controller unit under test, 4-521-01, SN 00x during the random vibration testing.

6.2.2.4 Vibration Testing Conclusion

With these vibration levels; workmanship and basic structural integrity has been confirmed without needlessly aging the unit. The expected mounting locations for the 4-520-01 during the systems evaluation phase (wheel bay) is substantially isolated from the normal vibration generation sources (engines, gun fire, aerodynamic buffeting, etc.). ELDEC concludes that the vibration test levels indicated will meet the need and intent of the 4-520-01 program for systems evaluation.

6.2.3 Temperature Testing

Thermal confidence testing was performed on a 4-521-01 to verify the unit capability and confirm similarity to the 4-254. Raw data were collected in ELDEC Design and Computation Notebook Number 367 issued to ELDEC Electronic Technician Rick Perrault.

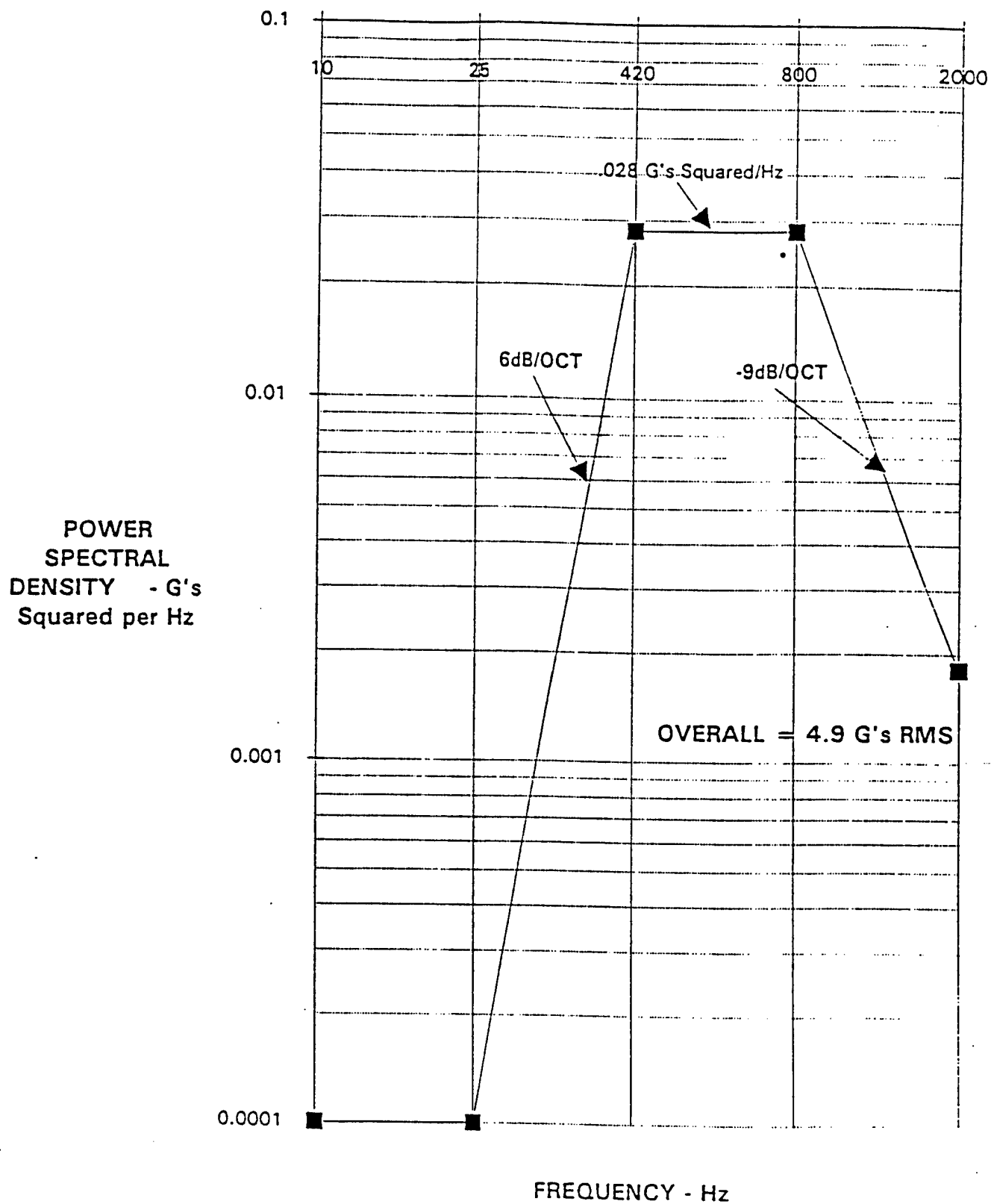
6.2.3.1 Conditions

Thermal testing was performed at room temperature (25°C), 40°C, 50°C, 60°C, and 70°C. In addition, cold start testing was performed at -40° C and -55°C. All testing was conducted at standard pressure.

¹ Note: This level represents the equivalent of a six month endurance test at the same level that the 4-254 originally qualified. At this level the unit is expected to remain functional and incur only about 5% of its normal lifetime of aging.

RANDOM VIBRATION TEST CURVE

FIGURE 6-2



6.2.3.2 Setup

- 1) For all temperature testing, the unit was placed on wood slats (to allow free convection air flow and eliminate conduction affects).
- 2) Thermal couples were placed on several high power devices, heatsinks and in air stream locations (see thermal map).
- 3) The unit was powered up to 40 amps output (base charge) for 30 minutes.
- 4) After 30 minutes, the output was reduced to 13 amps (over charge) with temperature readings continued for an additional 30 minutes (60 minutes total).

6.2.3.3 Results

- 1) The 4-521-01 successfully completed all room temperature and elevated ambient temperature tests described above.
- 2) All part temperature readings paralleled the ambient. That is; the 70°C component temperature readings were 10°C higher than the 60°C readings etc.
- 3) The highest temperature reached (during the 70°C test - after 30 minutes of base charge) was 110°C for the rectifier case temperature. All other part case temperatures were lower.
- 4) The 4-521-01 successfully completed cold start temperature testing at -40°C and -55°C.

6.2.3.4 Thermal Testing Conclusion

The 4-521-01 will operate in all sea level temperature environments from -55°C to 71°C at all loads up to 40 amps. It has been determined by analysis that the 4-521-01 will operate in all temperature-altitude environments within the envelope described in the thermal design capabilities section (paragraph 5.2.2.3).

6.2.4 Performance Testing

The charger/controller performance is verified by ELDEC Acceptance Test Procedure (ATP), document number ATP4-521. This document specifies test procedures, equipment and acceptance criteria to verify the charger/controller meets all physical and electrical requirements.

7.0 Battery Compatibility Testing

7.1 Test Plan

The battery compatibility testing was designed around the B-52 flight testing that was done as an extension of the original contract. The test plan was designed to simulate a 1-year operation on the B-52. The plan accelerates the testing into a 30- to 40-day test. The B-52 usage was based on the Boeing Wichita, Request for Budgetary Proposal Information document dated 28 March 1989, document number

3-ML1432-02-389-105/J1-389-009. This document has a Figure 5 and an Appendix A which describes the loading and a B-52G/H mission profile.

Table 7-1 shows the accelerated test requirements that were used for the compatibility testing. Requirement A represents accelerated READY status for the aircraft where intermittent unscheduled intervals draw low current from the battery in 20 minute increments. Requirement B represents a cartridge start for the airplane with the power supplied by the battery. Requirement C is basically used to represent a capacity check on the battery and it is done at different intervals to evaluate the battery's capacity as the test proceeds.

Table 7-2 shows the cycle description of the compatibility test. Each cycle represents an approximate 2-week period of operation. The test column describes the load (per Table 7-1) or the mode of operation. The duration is the approximate time for that particular sequence in the test. The description explains what test is run at that time. Because the test is accelerated, the battery is under much greater stress than it will be on the aircraft as far as cycles per day are concerned. In order to accommodate the extra stress in the battery, several rest periods are utilized to bring the battery to a steady-state condition prior to the next test mode within the cycle.

Table 7-3 shows the entire test sequence for the compatibility test. The test column describes the number of cycles or if a capacity check will be done (load per Table 7-1). The duration again is the approximate time for the particular test step. The temperature is the temperature that the battery will be held at during the test step. And the description explains what test is run. This test sequence covers 30 cycles as shown in Table 7-2 and simulates 1-year of accelerated life on the B-52.

7.2 Test Results

A summary of test results for the compatibility testing is shown in Table 7-4. This table covers two sheets, the first shows the charge/discharge data including charge efficiencies. The second sheet shows the battery temperature information at strategic points in the charge cycle during the testing.



TABLE 7-1

BATTERY COMPATIBILITY TESTING

ACCELERATED TEST REQUIREMENTS.

REQUIREMENT	TIME RATE	CUT-OFF VOLTAGE	DISCHARGE RATE (A)	CAPACITY (A-HRS)
A	35 MIN	20.0	25	14.58
B	30 SEC	18.0	100	0.83
C	1 HR	20.0	22	22



TABLE 7-2

BATTERY COMPATIBILITY TESTING

CYCLE DESCRIPTION

TEST	DURATION	DESCRIPTION
A	35 MIN	STANDBY LOADING
CHARGE	45 MIN *	CHARGE CYCLE
REST	60 MIN	REST CYCLE
A	35 MIN	STANDBY LOADING
B	30 SEC	CARTRIDGE START
CHARGE	60 MIN *	CHARGE CYCLE
REST	120 MIN	REST CYCLE

* APPROXIMATE TIME ONLY. WILL ALLOW FULL RECHARGE OF THE BATTERY.



TABLE 7-3

BATTERY COMPATIBILITY TESTING

TEST SEQUENCE

TEST	DURATION	TEMPERATURE (DEGREES C)	DESCRIPTION
C	2 HRS	24 (75°F)	CAPACITY CHECK
4 CYCLES	16 HRS	24 (75°F)	ROOM TEST
1 CYCLE	4 HRS	50 (122°F)	HOT TEST
6 CYCLES	24 HRS	24 (75°F)	ROOM TEST
C	2 HRS	24 (75°F)	CAPACITY CHECK
1 CYCLE	4 HRS	-18 (0°F)	COLD TEST
6 CYCLES	24 HRS	24 (75°F)	ROOM TEST
1 CYCLE	4 HRS	50 (122°F)	HOT TEST
6 CYCLES	24 HRS	24 (75°F)	ROOM TEST
C	2 HRS	24 (75°F)	CAPACITY CHECK
1 CYCLE	4 HRS	-18 (0°F)	COLD TEST
6 CYCLES	16 HRS	24 (75°F)	ROOM TEST
C	2 HRS	24 (75°F)	CAPACITY CHECK

TABLE 7-4

TEST RESULT SUMMARY

4-520 COMPATIBILITY TESTING
TOTAL TEST SUMMARY

DATE: 3-5-91

CYCLE #	TEMP DEG C	END VOLT 1ST DCHG	END VOLT 2ND DCHG	END VOLT CRTG START	A-H OUT DCHG	1ST BASE CHARGE A-H	1ST OVER CHARGE A-H	TOTAL 1ST CHG A-H	1ST CYC CHARGE EFFICIENCY	A-H OUT 2ND CHG	2ND BASE CHARGE A-H	2ND OVER CHARGE A-H	TOTAL 2ND CHARGE	2ND CYC CHARGE EFFICIENCY	NOTES / COMMENTS
CAP 1	25	22.00	22.00	N/A	22.25	23.52	1.834	25.586	101.329	N/A	N/A	N/A	N/A	N/A	START OF COMPAT - CAP TEST #1 (NO WARN LIGHT ON CAP DCHG)
1	25	24.69	24.48	22.83	11.55	12.420	0.928	13.348	114.484	12.56	12.066	1.718	13.784	108.574	NO FAILURE ON CRTG START
2	25	24.28	24.27	22.59	11.67	12.359	1.734	14.033	120.251	12.59	12.319	2.709	15.028	119.269	NO FAILURE ON CRTG START
3	25	24.09	24.14	22.38	11.67	12.500	2.285	14.785	126.887	12.58	12.106	3.857	15.963	126.395	NO FAILURE ON CRTG START
4	25	23.35	23.08	22.28	11.58	12.780	2.924	15.704	133.596	12.81	11.913	4.466	16.379	129.335	NO FAILURE ON CRTG START
5	25	23.52	23.54	21.79	11.66	12.993	3.190	16.204	141.316	12.80	11.406	6.261	17.667	140.213	1ST SO DEG. C COMPAT CYC (NO FAILURE ON CRTG. START)
6	25	23.29	24.10	22.22	11.57	12.953	3.490	16.163	145.009	12.60	11.278	6.117	17.396	138.064	NO FAILURE ON CRTG START
7	25	23.29	24.10	22.22	11.57	12.953	3.490	16.163	145.009	12.60	11.446	3.997	15.443	123.545	NO FAILURE ON CRTG START
8	25	23.14	23.15	21.90	11.64	12.456	3.423	15.881	135.931	12.60	11.599	3.201	14.800	117.459	NO FAILURE ON CRTG START
9	25	23.17	23.17	21.78	11.64	12.456	3.423	15.881	135.931	12.52	11.806	2.167	13.993	111.230	NO FAILURE ON CRTG START
10	25	23.46	23.46	21.34	11.57	11.893	2.816	14.709	124.425	12.31	11.899	2.632	14.531	115.239	NO FAILURE ON CRTG START
11	25	23.55	23.60	21.79	11.57	11.524	2.064	13.589	112.425	12.31	11.778	2.340	14.219	112.845	NO FAILURE ON CRTG START
CAP 2	25	22.00	22.00	N/A	20.30	18.590	2.871	22.261	109.832	N/A	N/A	N/A	N/A	N/A	2ND CAP TEST (WARN LIGHT ON BATV.22.0 V%)
12	19	21.69	24.11	22.04	11.57	10.519	1.828	12.155	104.210	12.40	10.868	1.371	12.750	91.5	1ST -18 DEG. C COMPAT CYC (NO FAILURE ON CRTG. START)
13	25	23.74	23.94	22.00	11.67	12.106	2.072	14.178	121.088	12.59	11.869	1.869	13.658	110.562	NO FAILURE ON CRTG START
14	25	23.69	23.34	21.35	11.60	11.779	1.849	13.728	117.524	12.60	11.859	2.047	14.008	111.159	NO FAILURE ON CRTG START
CAP 3	25	22.00	N/A	N/A	18.41	18.529	2.141	20.670	105.922	N/A	N/A	N/A	N/A	N/A	3RD CAP TEST (NO WARN LIGHT ON DCHG)
15	25	23.99	24.18	22.38	11.57	13.127	2.596	15.723	134.725	12.51	11.848	2.304	14.250	113.003	12 MIN. DCHG TIME LIMIT ADDED (PRIOR TO 1TH CAP TEST)
16	25	23.90	23.99	22.14	11.66	12.153	2.181	14.334	123.822	12.58	11.906	2.179	14.095	111.965	NO FAILURE ON CRTG START
17	25	23.74	23.90	22.04	11.66	12.106	2.272	14.383	123.355	12.50	11.733	2.229	13.962	111.393	NO FAILURE ON CRTG START
18	25	23.94	23.35	21.93	11.57	12.199	2.272	14.471	124.018	12.59	11.373	2.012	13.345	110.284	NO FAILURE ON CRTG START
19	50	23.81	22.91	20.35	11.57	7.604	2.246	9.850	65.092	12.49	11.388	2.143	13.542	108.421	2ND SO DEG. C COMPAT CYC (NO FAILURE ON CRTG. START)
20	25	21.96	23.90	21.95	11.66	15.448	2.208	17.656	151.182	12.59	12.032	2.267	14.339	113.395	NO FAILURE ON CRTG START
21	25	23.51	23.78	21.72	11.66	12.279	2.281	14.560	124.875	12.80	11.789	2.225	14.024	111.392	NO FAILURE ON CRTG START
CAP 5	25	22.00	N/A	N/A	14.84	15.394	2.018	17.412	116.938	N/A	N/A	N/A	N/A	N/A	CAP TEST #5 (DCHG "1" ONLY @ 16A P.M. 1/2 OF TEST)
CAP 6	25	22.00	N/A	N/A	17.26	16.076	2.312	13.737	117.718	N/A	N/A	N/A	N/A	N/A	CAP TEST #6 (NO WARN LIGHT DURING DCHG)
22	25	21.30	24.10	22.20	11.67	11.425	2.312	13.737	117.718	12.55	11.506	2.173	13.678	103.998	NO FAILURE ON CRTG START
23	25	23.67	23.97	21.91	11.67	12.279	2.248	14.525	124.072	12.51	11.745	2.266	14.011	112.002	FIX S.W. FOR SMOOTHER TR MODE TRAINING FAIL ON CRTG START
24	25	23.85	23.79	21.34	11.23	11.372	3.138	14.510	114.796	13.00	11.225	3.227	14.452	112.390	NO FAILURE ON CRTG START
25	25	23.32	23.70	21.30	11.37	12.533	2.231	14.764	125.312	12.57	11.399	2.271	13.670	111.142	NO FAILURE ON CRTG START
CAP 7	25	22.00	N/A	N/A	14.76	15.454	2.233	17.687	118.833	N/A	N/A	N/A	N/A	N/A	CAP TEST #7 (NO WARN LIGHT DURING DCHG)
26	25	23.70	23.70	21.70	11.66	12.456	2.122	14.617	119.343	12.51	10.345	1.720	12.085	98.147	2ND -18 DEG. C COMPAT CYC (NO FAILURE ON CRTG. START)
27	25	23.27	23.27	21.68	11.57	10.825	2.122	12.947	108.601	12.80	11.819	2.252	14.071	111.875	NO FAILURE ON CRTG START
28	25	23.27	23.63	21.48	11.67	11.893	2.131	14.121	128.601	12.80	11.819	2.252	14.071	111.875	NO FAILURE ON CRTG START
29	25	22.70	23.72	21.51	11.66	13.407	2.189	15.596	131.518	12.59	11.795	2.416	14.132	112.448	NO FAILURE ON CRTG START
30	25	23.15	23.56	21.37	11.66	12.093	2.173	14.266	122.800	13.00	11.813	2.319	14.019	111.269	NO FAILURE ON CRTG START
CAP 8	25	22.00	N/A	N/A	14.01	15.021	2.244	17.265	123.233	N/A	N/A	N/A	N/A	N/A	CAP TEST #8 (NO WARN LIGHT DURING DCHG)

The Engineering battery used in the test had one "weak" cell that was watched closely during the testing for evidence of degradation. As such the information in the notes column in Table 7-4 shows a "WARN" light indication where this cell dropped below 1V during discharge. The cell did not degrade appreciably different than the other cells in the battery, therefore, the battery performance was considered to be valid as if the "weak" cell did not exist.

During testing several parameters were modified in the charger software to better tailor the charging profile. These required modifications came from examination of the test data and battery/charger performance during the testing phase.

The two major changes in the software were modifications to the overcharge and TR mode of operation. The overcharge mode was modified to include, in addition to a cut off and roll over termination indication, a 12-minute time limit such that the overcharge will be limited in time was incorporated. This modification was incorporated after Cycle 14 just prior to the fourth capacity test. The second change was incorporated at Cycle 22 which reduced the TR mode voltage level at the battery to 26.5V and modified the transition from overcharge to TR mode for a smoother transition without excessive current draw from the battery.

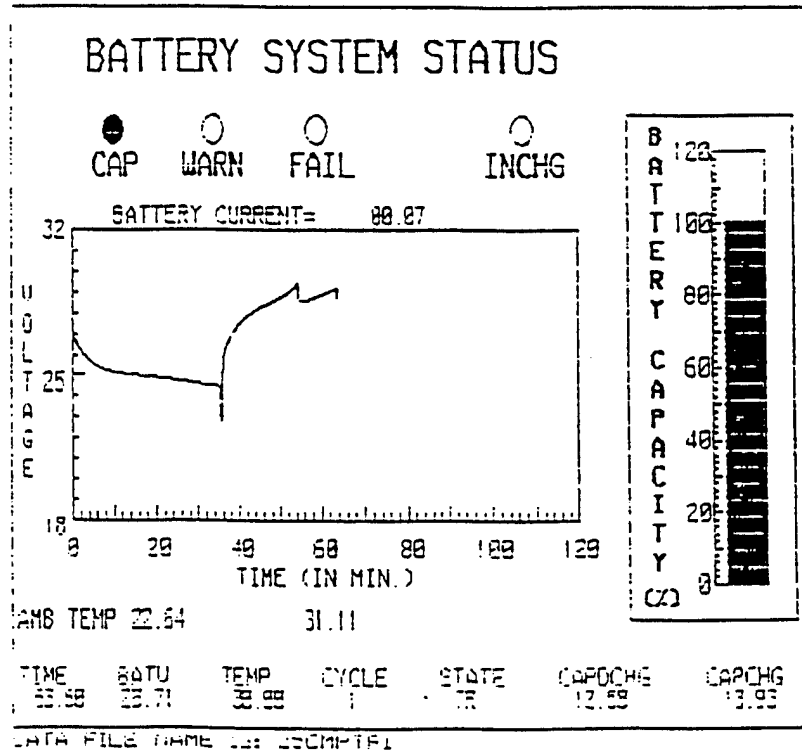
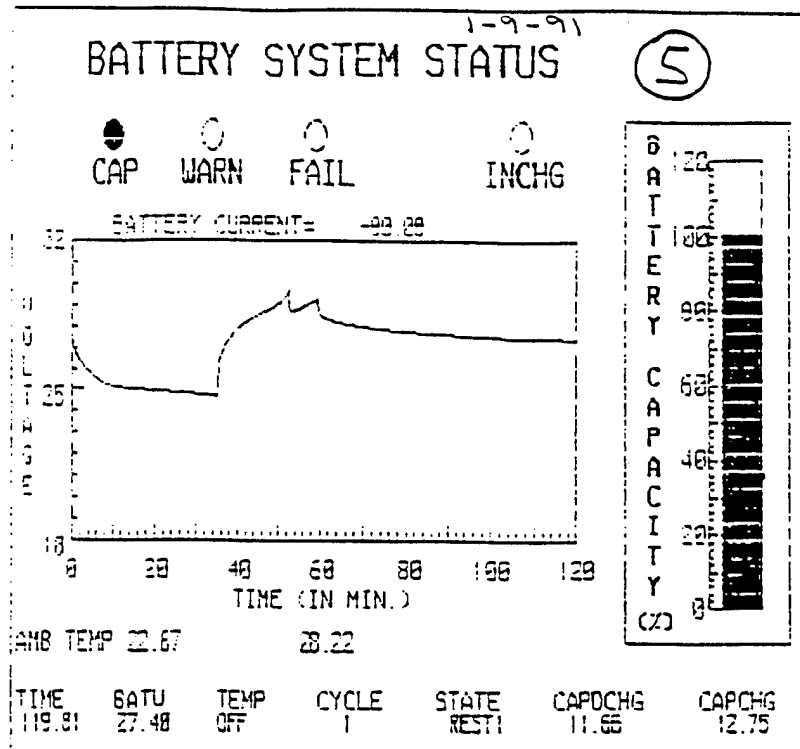
Several battery performance curves are summarized below:

Figure 7-1 Screen Dump from test station

This figure is a screen dump from the computer controlled test station showing one complete test cycle. The upper view shows the first discharge, charge and rest sequence. The lower view shows the second discharge with a cartridge start load of 100A at the end of the discharge (evidenced by the abrupt voltage drop) and then the final charge. One cycle was performed each day and then the battery was allowed to rest for 24 hours before the next cycle was run.

Figure 7-2 Temperature Comparisons

This figure shows three curves for a cartridge start discharge and charge subcycle. The curves are for -18, +25, and +50 degrees battery temperature. The figure shows about 1V of depression from the room temperature baseline to the hot temperature during discharge. The cold temperature performance during discharge is virtually identical to the room temp. During the cartridge start, there is only 0.5V difference between the temperatures. During the charge subcycle the cold temperature yielded the highest voltage, and at hot temperature, the voltage rolls over during overcharge. These curves also show the charger cutoff voltage as it is compensated to ensure adequate charging at the temperature extremes.



SCREEN DUMP

FIGURE 7-1

4-520 COMPATABILITY TEST HOT, COLD, AND ROOM TEMP COMPARISONS OF CARTRIDGE START SUBCYCLES

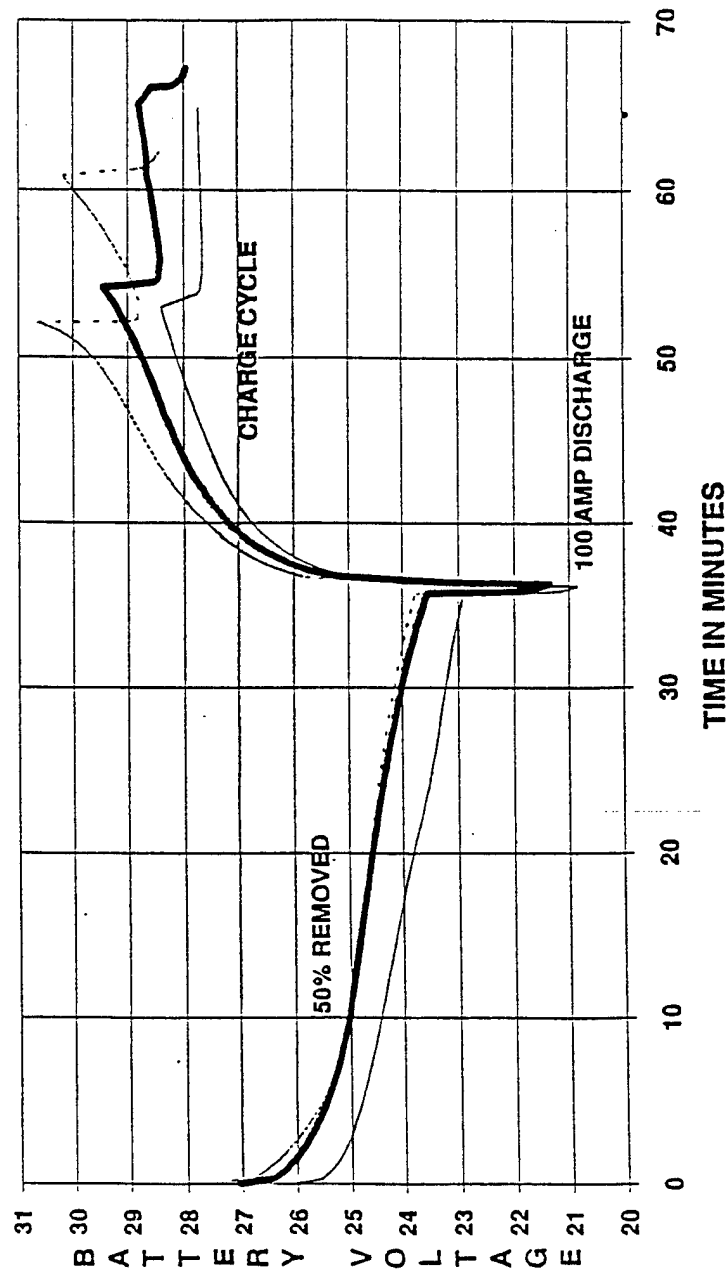


FIGURE 7-2

Figure 7-3 Discharge End Voltages

This figure shows the voltage of the battery vs. compatibility cycles at the end of each discharge subcycle and at the end of the cartridge start. The curve for the first discharge (DCHG1) shows a large dip at cycle 20 which was caused by a long rest period (after a weekend) just after a hot cycle. However, the voltage came back in alignment after a few additional cycles. These data show that the end voltage dropped about 1V during the entire test sequence. The cartridge start data basically follows the DCHG2 curve only it is another 1.5V below due to the higher current discharge.

Figure 7-4 Start and End Comparison

This figure shows the first and last cartridge start subcycles which shows the voltage depression during discharge. Of note here is the slope change during discharge which indicates a capacity degradation in the battery. The charge cycle looks the same for the base charge region; however, the voltage is depressed for the overcharge region.

Figure 7-5 Capacity Fade Data

The voltage drop indications are caused by a capacity fading effect in the battery. This figure shows the capacity as a function of cycles where cycle 1 was performed prior to the compatibility testing and cycle 8 was performed after the compatibility testing. These data indicate considerable fading in the battery as a result of this test sequence. The initial drop in capacity is believed to be caused by overcharging of the battery in the overcharge region, and the charge regime was altered to correct for this as mentioned earlier. However, the capacity continued to fade further as the testing progressed with a final capacity of around 14 Ahs. This test was quite extreme with a 50 to 75% depth of discharge drained from the battery on each cycle which was to represent an accelerated life on the B-52. However, in reality the battery will typically only see a 10 to 20% depth of discharge between cycles and they will be extended considerably in time. Other data on the battery show with shallower depths of discharge that the capacity fading is not severe, in fact it is very slight; therefore, we believe that the battery will provide good performance for the 3-year time frame based on that observation.

4-520 COMPATABILITY TEST DISCHARGE END VOLTAGES

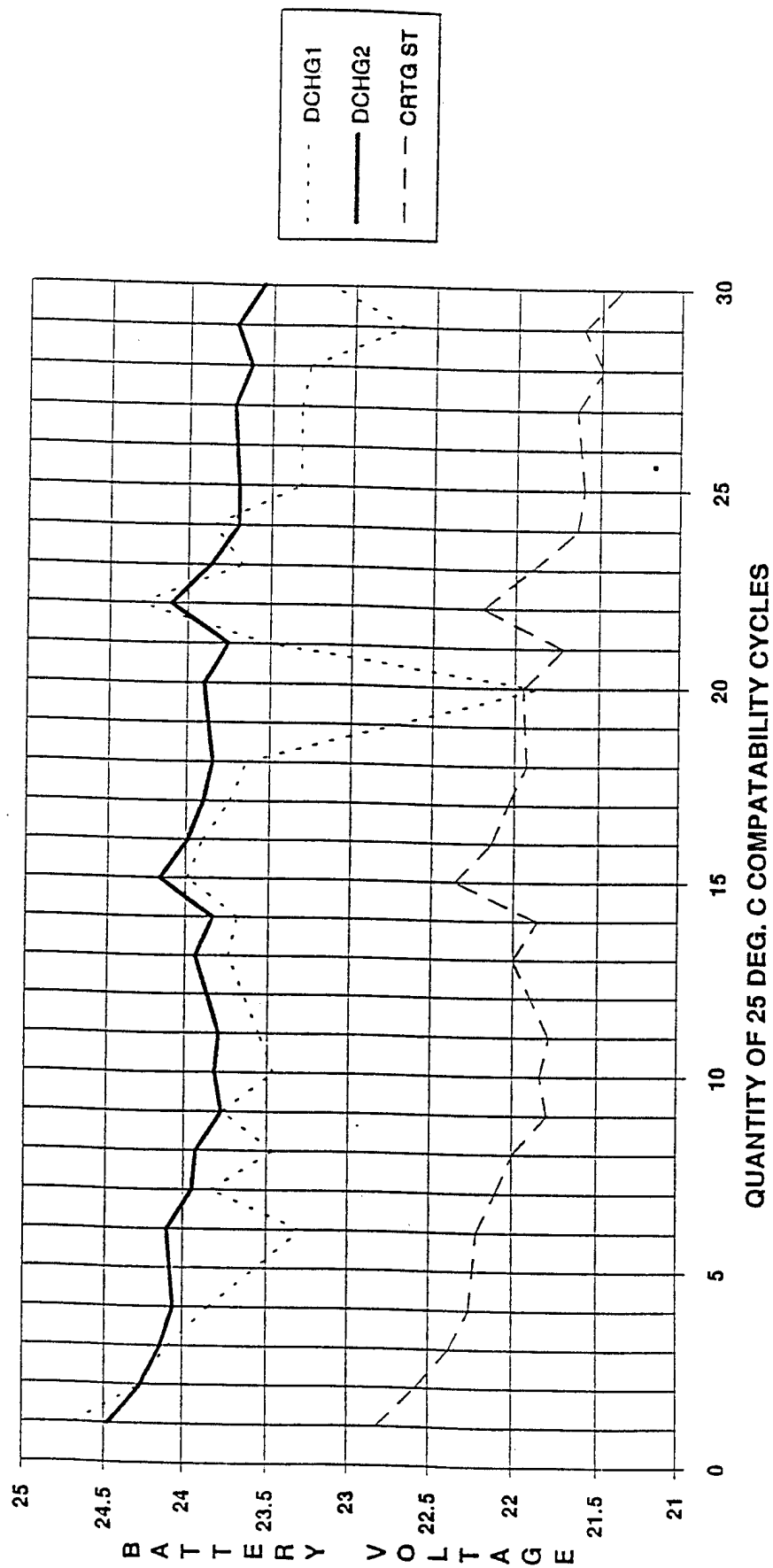


FIGURE 7-3

4-520 COMPATABILITY TEST 1ST AND 30TH CYCLE COMPARISONS FOR CARTRIDGE START SUBCYCLES (START AND END COMPARISON)

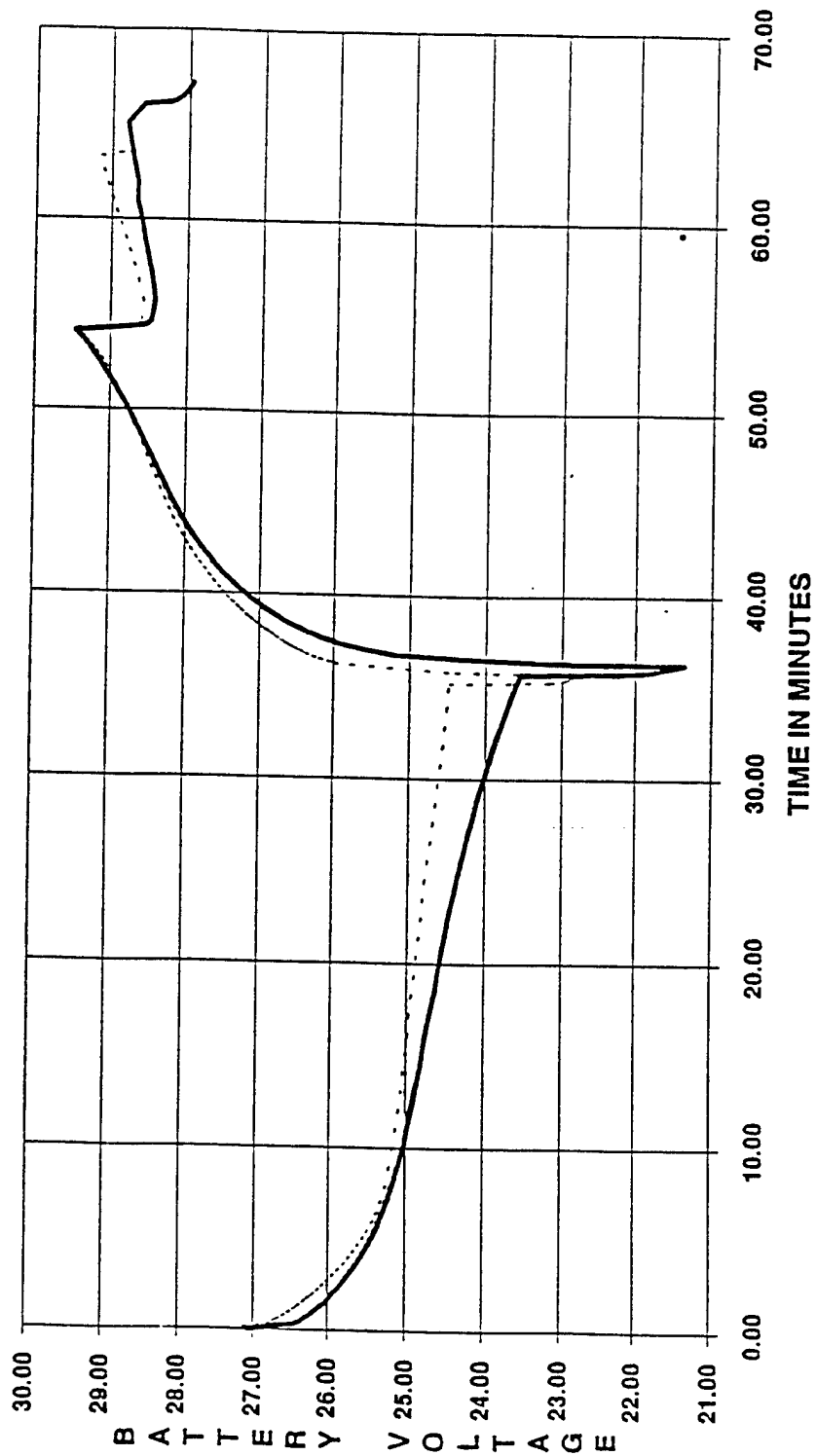


FIGURE 7-4

4-520 COMPATABILITY TEST CYCLES (CAPACITY FADE DATA)

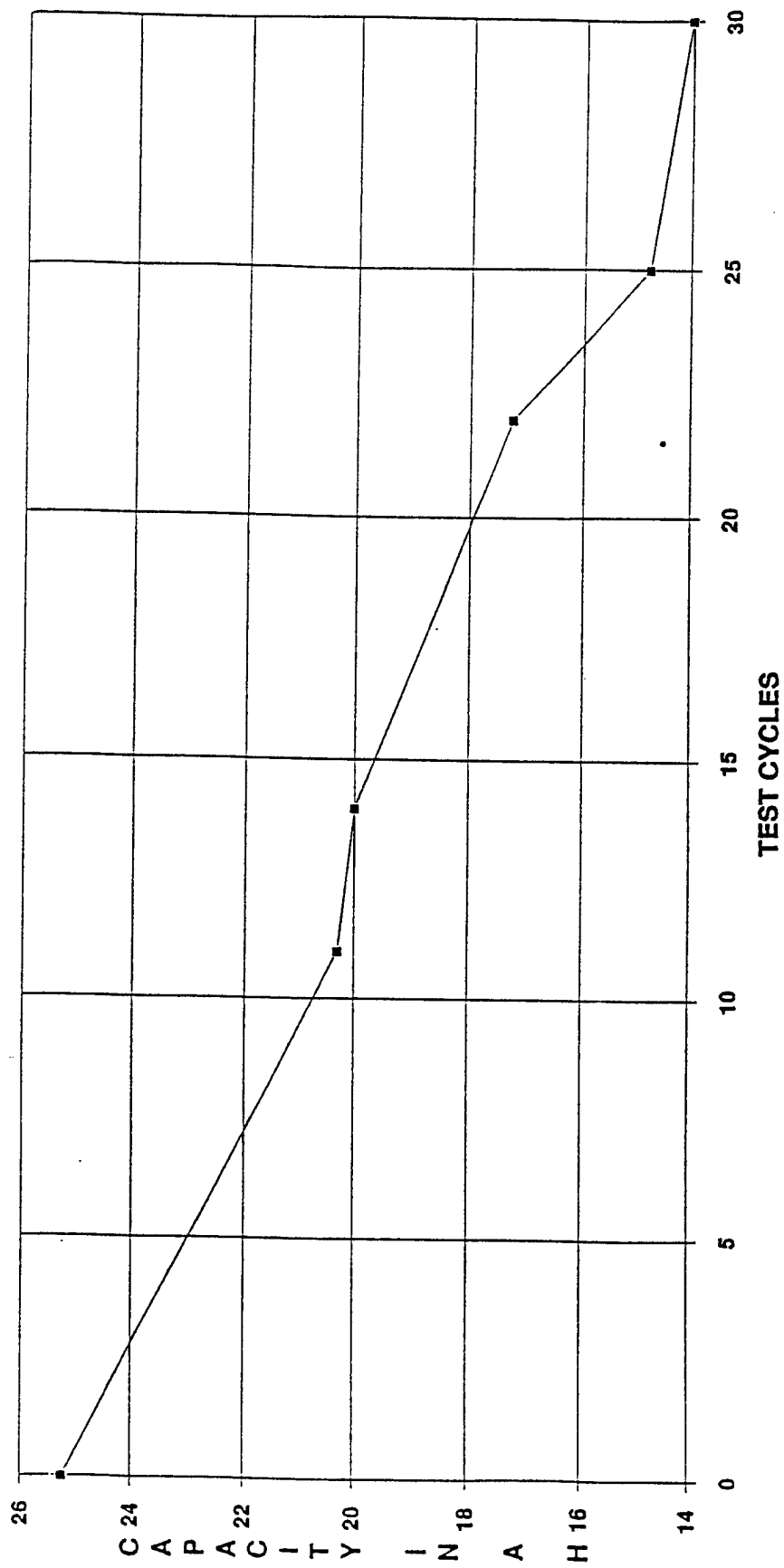


FIGURE 7-5